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ASSESSMENT OF JP-8 AS A REPLACEMENT FUEL FOR THE AIR FORCE STANDARD JET FUEL JP-4. PART I. ASSESSMENT OF JP-8/JP-4 FUEL IN NONCOMBAT ENVIRONMENT

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Air Force Aero Propulsion Laboratory
Wright-Patterson Air Force Base, Ohio

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This report is an assessment of JP-8 as a replacement fuel for the Air Force standard jet fuel JP-4. All facets of the problem are examined including fire safety under combat and noncombat conditions, crash fire safety, storage, handling and maintenance safety, laboratory testing, gunfire testing, flight testing, cost and availability, and impact on current Air Force weapons systems. The report concludes that a significant improvement in overall fire

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) safety could be achieved by conversion to JP-8 however, additional investigation into problems related to low temperature ground start and altitude relight should be accomplished prior to conversion.

FOREWORD

This report is an assessment of JP-4/JP-8 related efforts conducted by the Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio under Project 3048 "Fuels, Lubrication and Fire Protection". In addition, all other known efforts bearing on the JP-4/JP-8 decision have been reviewed and are presented where appropriate. The assessment of JP-8 as a replacement fuel for the Air Force standard jet fuel JP-4 was accomplished by an Ad Hoc Group formed with personnel from the Air Force Aero Propulsion Laboratory (AFAPL) and Aeronautical Systems Division (ASD) in June 1972. Mr. R. G. Clodfelter, AFAPL/SFH, was selected as chairman and other members of the JP-4/JP-8 Ad Hoc Group included: G. T. Beery and G. W. Gandee of AFAPL/SFH; J. L. Morris and J. R. McCoy of AFAPL/SFF, D. C. Wight, J. K. Klein and T. O. Reed of ASD/ENJPF; and D. M. Spear of ASD/ENJET. Also participating in the assessment were: C. R. Schaffnit of ASD/ENJPF, J. W. Moran of ASD/ENCSF, Capt. B. E. Esterby of ASD/XROA, A. J. Holten of the Air Force Flight Dynamics Laboratory/PTS and W. W. Ryan of ASD/ENJET.

Part II of this report contains the fuel vulnerability in a combat environment portion of the study. Part II is classified SECRET.

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

SECTION I

INTRODUCTION

When there is an aircraft accident involving damage or loss, a high probability exists that fuel fire and/or explosion is either the primary cause or a contributing cause. This is true in both the natural and combat environments. In the natural environment the average annual cost of fuel related fires in Air Force jet aircraft is a conservative $40 million. In the combat environment the annual cost is many times higher. Combat losses directly related to fuel fires and explosions resulted in the submission in 1967 of a Required Operational Capability by the Tactical Air Command (ROC #TAC-32-67) and associated Requirements Action Directive (USAF-RAD 8-25-1) dated 25 July 1967. One means for enhancing aircraft survivability is to utilize a fuel which is less susceptible to fire and explosion.

The selection of candidate fuels is limited to conventional hydrocarbons having the required availability, reasonable cost, and suitable physical and chemical properties to permit direct utilization in operational aircraft without the need for extensive system modifications or serious degradation of flight performance. The above factors immediately exclude modified fuels such as gels and emulsions from any serious consideration for the near future. Aviation fuels currently utilized for military and commercial applications can be categorized into three basic types: (1) Aviation Gasoline, (2) Jet B (Air Force JP-4), and (3) Jet A (includes JP-8 and JP-5) and are often referred to as high volatility, intermediate volatility and low volatility fuels, respectively. Other than the difference in volatility, freeze point, and viscosity, the jet fuels possess similar properties. The relative fire safety of the various jet fuels, particularly under aircraft crash environment conditions, has been a long-standing controversy (References 1 and 2). Until recently, only minimal effort has been devoted to the assessment of the effect of volatility on the relative vulnerability of fuels to gunfire. Gunfire tests conducted by the Air Force in 1968, utilizing 50 caliber incendiary projectiles fired into the liquid space of small fuel tanks, demonstrated a possible operational advantage for the low volatility fuels compared to JP-4. Extensive additional investigations have recently been completed and are discussed in this report.

The intent of this report is to provide an assessment of low volatility fuel JP-8 as a replacement for the Air Force standard jet fuel JP-4.

Although the original motivation for considering JP-8 as a replacement fuel for JP-4 was to enhance aircraft combat survivability many other factors, related to both current and future aircraft and fuel technology, have been examined. Combat survivability has evolved as just one of many equally important factors to be weighed in any decision to convert to JP-8. These additional factors include general aircraft safety, fuel handling, aircraft and engine design and performance, DoD and international interchangeability, fuel availability, and cost.

SECTION II

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

a. A large segment of Air Force aircraft accidents and fatalities both in-flight and during ground maintenance and servicing operations involve JP-4 fuel fires and explosion. Analysis of Air Force aircraft combat loss data indicates gunfire induced fuel system fires and explosions to be the principal cause factor.

b. For conditions encountered during the major portion of normal aircraft ground and flight operations, a low volatility fuel such as a JP-8 offers a significant fire safety advantage over higher volatility fuels such as JP-4. Realization of this safety advantage is, of course, contingent on the continued rigorous adherence to established safety procedures.

c. Analysis of aircraft combat loss and battle damage data and in particular the results of controlled ballistic testing of various volatility jet fuels indicate the JP-8 should provide inherently reduced vulnerability to damaging fires and explosions. JP-8 of itself does not negate the fire and explosion problem but, when utilized in conjunction with other established fire and explosion protection measures, provides an overall superior aircraft combat survivability posture compared to JP-4.

d. Conversion to JP-8 would virtually eliminate the raw hydrocarbon vapor emissions problem currently confronting the Air Force with JP-4 and result in a substantial cost savings.

e. As a result of the energy crisis the entire turbine engine fuel availability and cost picture is in a state of flux. In general, the availability and cost advantages previously always associated with the wider-cut, more volatile JP-4 fuel are disappearing and in the long-term these advantages will belong to the lower volatility, JP-8 type fuel.

f. Conversion to JP-8 would provide the Air Force and the Army with a product which, with the exception of the anti-icing and corrosion inhibitor additives, is similar to Civil Aviation Jet A-1 fuel, and represents the major step toward the realization of world-wide fuel standardization with its attendant logistic capability and overall cost savings advantages.

g. On the negative side, adoption of JP-8 would degrade current aircraft system low temperature start-up and altitude relight capabilities. Flight tests have shown that different systems will be affected differently when operated on JP-8 fuel. Engine modifications will be required. Full assessment of the operational and cost impact requires in-depth evaluation and could be affected by the particular time phased conversion plan selected for JP-8.

2. RECOMMENDATIONS

a. The Air Force pursue a course of action directed towards world-wide Air Force utilization of JP-8 jet fuel.

b. A comprehensive plan should be developed leading to the systematic conversion to JP-8. The plan will require assessment of the impact of this conversion on engines, auxiliary power units and ground power equipment currently using JP-4. In particular, investigations must be conducted in the areas of low temperature ground starting as well as altitude relight.

c. That the Joint Technical Coordination Group (JTCG) on Fuels Standardization currently established under the Joint Logistics Commanders be directly concerned with development of a plan to convert from JP-4 to JP-8 jet fuel.

SECTION III

JET FUEL BACKGROUND AND FUEL PROPERTIES

1. JP-1 THROUGH JP-4

History of gas turbine engine fuel dates to 1944 with the introduction of JP-1. This -76°F freeze point fuel, having a 300°F to 500°F boiling range, could not be produced in sufficient quantities to meet military requirements. In an effort to increase availability, a wider cut fuel, JP-2, was authorized in 1945. JP-2 was used only for experimental purposes as viscosity restrictions limited its production. The availability problems posed by JP-1 and JP-2 resulted in the adoption of JP-3 in 1947. JP-3 was produced by blending gasoline with kerosene. It was found that while fuel requirements could be met, the relatively high Reid vapor pressure of 7 psi caused excessive losses in the order of 20 percent by venting of liquid and vapor in high rate of climb aircraft and at high altitudes. For these reasons a specification for JP-4, which essentially is a low vapor pressure JP-3, was issued in 1951 and at present is the standard USAF jet fuel.

While there have been refinements to the fuel specification to keep pace with engine developments, JP-4 has basically maintained the critical properties first specified to insure availability and to fulfill aircraft operational performance requirements. JP-4 is a wide cut mixture of heavy naphtha and kerosene with an average 140°F to 460°F boiling range. It possesses a maximum freeze point of -72°F and a Reid vapor pressure of 2 to 3 psi at 100°F, a compromise volatility that assures availability with reduced vaporization loss. Related to the volatility is an expected low flash point of approximately -20°F and an explosive range from approximately -20°F to 70°F under equilibrium conditions.

2. JP-5

The need for a less fire-hazardous fuel aboard aircraft carriers was responsible for the adoption of JP-5 by the US Navy in 1952. It is considered the standard US Navy fuel, although approximately 23 percent of the fuel consumed by the Navy is JP-4. Properties of JP-5 affecting ignitability are a boiling range of 300°F to 550°F, a freeze point of -51°F, and a flash point requirement of 140°F minimum.

The narrow boiling range of JP-5, combined with the 140°F minimum flash point requirement, are severe limitations in the production capability of this fuel. FY 75 projected consumption of JP-5 by the military will total approximately 1.23 billion gallons (20%) compared to 5.05 billion gallons (80%) for JP-4. JP-5 as a replacement fuel for JP-4 would decrease jet fuel availability by approximately 70 percent. The petroleum industry has verified that it cannot support the requirement that a conversion to JP-5 would demand.

3. JET A AND JET A-1

In 1958 the American Society for Testing and Materials (ASTM) formulated commercial jet fuel specification D-1655. Requirements for Jet A and Jet B (JP-4) were specified. Jet A was used almost exclusively by commercial carriers within the CONUS in order to enhance ground and flight safety. Its properties include a 105°F minimum flash point requirement and a freeze point of -40°F. Long-range, high-altitude aircraft operations made it necessary to formulate a lower freeze point kerosene. Approximately one year later Jet A-1, having identical properties to Jet A except for a -58°F freeze point requirement, was added to the commercial specification.

The freeze point requirement of -40°F eliminates Jet A as a candidate replacement fuel for JP-4. Sustained high-altitude USAF flight profiles have shown that fuel temperatures below this figure are experienced. Use of Jet A would require a significant realignment of flight profiles and in turn reduced mission capabilities to insure safe flight operations or require major system redesign to permit use of this fuel where freezing conditions would be encountered for prohibitive periods.

4. JP-8

Efforts to evaluate the use of a safer fuel than JP-4 for combat operations, as well as ground handling, were intensified with the Southeast Asia conflict. Combat losses directly related to fuel fires or explosions resulted in the submission in 1967 of a Required Operational Capability by the Tactical Air Command (ROC Number TAC-32-67). The subsequent Requirements Action Directive (USAF-RAD-8-25-1) supported the basis for evaluation of a more combat safe fuel. JP-8, which is essentially commercial Jet A-1 with fuel system icing inhibitor and corrosion inhibitor added, was selected for further tests in 1968. Initially, considered as a possible replacement fuel for JP-4 in Southeast Asia (SEA), its expanded use for USAF application worldwide has been proposed. Significant and favorable volatility properties of JP-8 are a vapor pressure of <0.10 at 100°F and a minimum flash point of 105°F, which normally exceeds ground handling temperatures. Also it appeared that JP-8 would be available in the quantities required. Thus, JP-8 emerged as a prime candidate fuel.

5. SPECIAL APPLICATIONS

a. Grade JP-5 is the preferred fuel for Presidential aircraft (Reference 3). Alternate fuels in their order of preference are Jet A-1, Jet A and JP-4. Grade JP-5 used specifically for AF No. 1 contains FSII (Fuel System Icing Inhibitor). Grade JP-5 is used in this case to maximize safety.

b. As a result of the explosion of a fuel tank and subsequent loss of a C-5A (#1) during maintenance at Lockheed Aircraft Corporation during October 1970 (accident attributed to human error), Lockheed was permitted to change from JP-4 to JP-5 fuel (some limited use of Jet A-1 is also permitted). It was concluded by the accident investigation team that, given the same conditions, this aircraft valued at over $100,000,000 would not have been destroyed if JP-5, JP-8, Jet A or Jet A-1 was the operational fuel.

6. COMPARISON OF FUEL PROPERTIES

Properties of general interest are given in Tables I through VIII. The values for Jet A-1 will indicate what properties may be expected for JP-8. A DoD conversion, in competition with the commercial airlines for kerosene type fuel, may shift properties toward higher volatility. On the other hand, demand in other industries for the gasoline type fractions may offset any shift due to increased kerosene demand.

The advantage/disadvantage factors (safety, cost, low temperature operation, engine starting, smoke, etc.) associated with JP-8 are in between those of JP-4 and JP-5. This is important since throughout the report when direct comparisons between JP-4 and JP-8 are not available, JP-4 and JP-5 may be compared. For example, the J79 engine low smoke combustor showed a 5 point increase for JP-5 compared to JP-4. There was no smoke data for JP-8 therefore the expected increase in smoke point for JP-8 would be 5 or less.

Flash point range, not average, is given in Table V and the impact of both the minimum and maximum has to be considered. Low flash is the worst case for fire related areas. High flash is the worst case for cold starting.

All jet fuels have about the same gravimetric (Btu/lb) heating values but the kerosene fuels have substantially higher volumetric (Btu/gal.) heating values as reflected below in Table VI. Grade JP-8 (Jet A-1) will increase range per mission but probably at the sacrifice of payload in current systems. This higher heating value may have more benefit in the design of future systems.

Grades JP-4 and Jet B have the same distillation requirement. The same holds also for Jet A, Jet A-1, JP-8, and JP-5 (Table VII). Grade JP-5 with a 140°F minimum flash point has only a 135°F typical boiling range which accounts for its limited availability (Table VIII).

TABLE I

DENSITY, LBS/GAL, 60°F

Fuel	Minimum - Maximum	Typical
JP-4	6.25-6.68	6.35
Jet B	6.25-6.68	6.34
Jet A	6.46-6.99	6.76
Jet A-1	6.46-6.99	6.68
JP-8	6.46-6.99	-
JP-5	6.56-7.03	6.80

TABLE II

VISCOSITY, CENTISTOKES, -30°F

Fuel	Maximum	Typical
JP-4	-	2.83
Jet B	-	3.08
Jet A	15	9.12
Jet A-1	15	7.74
JP-8	15	-
JP-5	16.5	10.5

TABLE III

FREEZING POINT, °F

Fuel	Maximum	Typical
JP-4	-72	below -80
Jet B	-58	below -76
Jet A	-40	-51
Jet A-1	-58	-59
JP-8	-58	
JP-5	-51	-56

TABLE IV

COMPOSITION, VOLUME %

Fuel	Aromatics		Olefins		Naphthalenes	
	Maximum	Typical	Maximum	Typical	Maximum	Typical
JP-4	25	11.8	5	1.0	3	.90
Jet B	20	10.1	5	1.5	3	1.20
Jet A	20	16.3	5	1.2	3	1.80
Jet A-1	20	13.9		1.1	3	
JP-8	25		5		3	
JP-5	25	16.0	5	0.8	3	1.60

TABLE V

FLASH POINT °F

Fuel	Minimum	Maximum	Typical Range
JP-4	-	-	Subzero
Jet B	-	-	Subzero
Jet A	105	150	108-148
Jet A-1	105	150	118-132
JP-8	105	150	-
JP-5	140	-	140-158

TABLE VI

HEAT OF COMBUSTION

Fuel	Btu/lb		Btu/gal	
	Minimum	Typical	Minimum	Typical
JP-4	18,400	18,727	115,000	118,916
Jet B	18,400	18,777	115,000	119,046
Jet A	18,400	18,583	118,864	125,621
Jet A-1	18,400	18,637	118,864	124,495
JP-8	18,400	-	118,864	-
JP-5	18,300	18,526	120,048	125,977

TABLE VII

DISTILLATION, SPECIFICATION MAXIMUM TEMPERATURE, °F

	JP-4, Jet B	Jet A, Jet A-1 JP-8, JP-5
Initial Boiling Point	-	-
10% Recovered	-	400
20% Recovered	290	-
50% Recovered	370	450
90% Recovered	470	-
End Point	-	550

TABLE VIII

DISTILLATION, TYPICAL BOILING RANGE, °F

Fuel	Initial Boiling Point	End Point	Difference
JP-4	142	456	314
Jet B	132	483	351
Jet A	331	512	181
Jet A-1	329	501	172
JP-8	-	-	-
JP-5	364	506	142

Grade JP-4 has an average initial boiling point (IBP) of 140°F at 1 atmosphere and IBP's as low as 115°F can be expected. IBP is significant as the trend to increased usage of the fuel as a coolant for airframe equipment is driving fuel temperatures beyond the IBP of JP-4 resulting in increased boiloff and cavitation problems.

Grade JP-4 has a 2 to 3 psi vapor pressure requirement at 100°F while the kerosene fuels have no vapor pressure requirement. All of the fuels discussed above have the same thermal stability requirement.

SECTION IV

RELATIVE VULNERABILITY ASSESSMENT OF JP-4, JP-5, AND JP-8

From a historical point of view it has been common practice to assess the hazards associated with a fuel by comparing the equilibrium flammability range (lean limit to rich limit) with the expected aircraft fuel temperature envelopes. Unfortunately, the determination of equilibrium flammability limits is not an exact science. Flammability is defined as self-propagating combustion. How "self-propagating" is defined is critical to the experimental results. It is well known that upward flame propagation is easier to obtain than downward flame propagation. Also, the term propagation implies some length or time criteria. In addition, the ignition source may affect the apparent measure of self-propagation. The point to be made is that there is no absolute equilibrium flammability range that applies to all conditions.

The flash point temperature of a liquid fuel is determined by exposing the vapors above it to an ignition source as temperature is increased, until there is a momentary flash. Flash point temperature is often erroneously equated to the lower limit of flammability and is in error for three reasons. First, because downward propagation is required; second, because there may be some loss of light-end fuel vapors during the test due to the repeated application of the pilot flame; and third, the light-end fuel constituents may not have sufficient time to vaporize since the flash point test is a dynamic test. The discrepancy may be as much as 25°F (Reference 4). This discrepancy may be reduced to a few degrees by proper specification controls.

The foregoing discussion may be somewhat academic since the real question is: "Is the pressure rise due to combustion sufficient to cause structural damage?" Many other factors are involved in this question, therefore, the following flammability limits are based on the historical use of flash point for the lower equilibrium flammability limit. For JP-4 the equilibrium flammability range (sea level) will be somewhere between -20°F and 85°F depending on the particular fuel sample and its aging history whereas for the proposed JP-8 the equilibrium flammability range (sea level) will be somewhere between 105°F and 185°F. Although there is no "standard" test procedure for determining flammability limits for hydrocarbon fuels, the type of information presented above is widely used to assess fuel vulnerability. As will be shown later in this section, these limits are of little value in assessing fuel vulnerability in the dynamic environment associated with an aircraft. It is well known that the "lean limit" of flammability for jet fuels can be effectively lowered by an addition of fuel spray or mist to the fuel tank ullage. Fuel tank slosh and vibration is one mechanism by which this can occur. Fuel/projectile interaction is another. On the other hand fuel tank venting tends to drive the ullage fuel-air mixture lean thus effectively increasing the "rich limit." It is extremely difficult to quantitatively define the actual environment inside a fuel tank of any operational aircraft at any given time, however, most persons concerned with aircraft safety agree that at conditions encountered during most aircraft operations low volatility fuels such as JP-8 are in general safer than high volatility fuels such as JP-4.

This safety advantage applies to the natural flight hazards crash situations, and the combat environment. It should be noted however that this safety advantage does not apply across the board to all conditions associated with the many different aircraft configurations and the many possible hazardous environments. There are a limited number of possible hazardous situations where JP-4 is the preferred fuel. Therein lies the problem of quantitatively assessing the relative safety difference between the two fuels. No two aircraft accidents or combat losses are alike. It is well known, however, that a very high percentage of aircraft losses (natural and combat) are due to fire and explosions.

Even if it was possible to adequately define a real aircraft hazard situation and all related factors so that comparison tests could be conducted with the two fuels, the test results would be questionable when applied to other hazard conditions. The point to be made is that many factors are unknown, the range of possible conditions is very large, and any test results which directly compares the two fuels is a measure of relative safety so long as the following conditions are satisfied:

(1) The test effort was a reasonable simulation of conditions possible on board an aircraft and

(2) The test results were a true measure of a difference between the two fuels and the difference was not due to experimental chance.

With the foregoing thoughts in mind, all pertinent test efforts designed to assess the relative combat vulnerability of the two fuels will be reviewed. Since it is beyond the scope of this report to develop aircraft/mission/threat scenarios, no attempt will be made to extrapolate from the test results to the conclusion that "x" number of aircraft and associated "y" dollars will be saved per year if JP-8 is used in place of JP-4.

1. INITIAL TESTS (REFERENCE 5)

As part of Project 3048 "Fuels, Lubrication and Fire Protection" the Air Force Aero Propulsion Laboratory (AFAPL), in 1967, initiated exploratory development efforts to reduce the vulnerability of JP-4 to gunfire. One of these efforts involved CAL .50 API (Armor Piercing Incendiary) tests allowing direct comparison of high and low volatility fuels. A small test tank approximately 17 gallons in capacity was devised which simulated a fuselage type fuel tank. The projectile was fired horizontally at various velocities and impacted the striker plate (aircraft skin) at an angle such that incendiary burning in the void space between the striker plate and the fuel tank occurred during all of the tests. The tank contained eleven gallons of fuel and tank penetration occurred below the liquid-vapor interface. The tests were conducted at ambient pressure conditions with the bulk fuel temperature and the projectile velocity being the principal variables. The main response variable was the type of fire that resulted from the projectile/fuel tank interaction. This experiment was designed to assess only the fire problem upon projectile penetration of the fuel tank and not internal to the fuel tank nor on the exit side of the fuel tank. When the pertinent tests were grouped by fuel type the results shown in Table IX were obtained:

TABLE IX

LIQUID FUEL .50 CAL GUNFIRE TESTS

FUEL	TOTAL TESTS	% NO REACTION	% FLASH FIRES	% FIRES SUSTAINED
JP-4	86	30.2	1.2	68.6
JP-8 (118°F flash point)	65	23.1	73.8	3.1
JP-5 (140°F flash point)	51	23.5	76.5	0
Test Conditions:	CAL .50 API Horizontal Gunfire, 17 gallon tank (11 gal. fuel) Velocity Range: 1690-2995 ft./sec, Fuel Temperature Range: 25°F-115°F			

Flash fires were defined as short duration reactions (≤ 2 seconds) which, if in a confined volume, could in some cases result in sufficient overpressure to cause structural damage to the test article. In this particular effort the reaction volume was open on four sides and therefore overpressures were not recorded. Flash fires were always self-extinguishing. Sustained fires were defined as fire which continued to burn at the test article and would most likely lead to structural failure of the test article.

This test effort clearly illustrated a tendency for JP-4 to be more susceptible to sustained external fires adjacent to fuel tanks (68.6 vs 3.1%). The reason for this being directly related to the high vapor pressure of JP-4 fuel and thus the high availability of fuel vapors to feed the fire. It should be noted that liquid fuel will not burn. Fuel spray and associated vapors generated by the projectile are what cause the initial fire ball for both fuels but since additional fuel vapor is not immediately available with JP-8, a low percentage of sustained fires were observed with this low vapor pressure fuel. The overall probability for some type of fuel reaction (either flash or sustained) was 69.8% for JP-4 and 76.9% for JP-8. From a statistical standpoint there is no difference between these two percentage figures. The damage potential associated with the flash fire will be discussed in detail in the next section.

2. VULNERABILITY OF DRY BAYS ADJACENT TO FUEL TANKS UNDER HORIZONTAL GUNFIRE (REFERENCE 6)

In order to assess the damage potential associated with flash fires an extensive gunfire program was initiated under contract with the FAA(NAFEC) Atlantic City, New Jersey, in 1969, by the Air Force Aero Propulsion Laboratory. This effort involved thirty different sets of test conditions for each of the two fuels, JP-4 and JP-8. Each set of test conditions was normally repeated four times for each fuel. In simplest terms, the test effort may be described as follows:

A CAL .50 API was shot horizontally at 2400 ft/second impacting a dry bay (volume varied between 0.44 ft^3 and 19.9 ft^3) with a ventilation rate in the dry bay ranging between 0 and 1225 ft^3/min. The projectile then impacted the fuel tank (~ 90 gal. 2/3 fuel) 9 inches below the liquid vapor interface. External airflow over the entire test article was varied between 0 and 300 knots and was generated by ducting fan air from a TF33 engine. For the bulk of the testing the fuel temperature was maintained at 90°F ±5°. There also were some additional variations in the foregoing general test conditions. A total of 252 tests were conducted in the program with the following results:

a. Thirty different sets of test conditions were evaluated for each fuel and in seven of these a significant difference occurred ($\geq$90% confidence level) in the dry bay overpressure between the two fuels. For these seven cases JP-4 had mean overpressure of 18.7 psi compared to 7.2 psi for JP-8.

b. For the "Standard Tests" (i.e. all test cases with the dry bay on the projectile entrance side) JP-4 gave higher dry bay overpressure than JP-8 at the 97.5% confidence level. The mean value was 11.8 psi (σ = 12.0 psi) for JP-4 and 8.5 psi (σ = 7.4 psi) for JP-8.

c. It was determined by analysis of the dry bay overpressures that on the average JP-4 had 2.5 times as much damage potential as JP-8. Actual test article damage experience during the test program was 2.4 times higher with JP-4 compared to JP-8.

d. 11.28% of the tests resulted in sustained external fires with JP-4 whereas the value was only 1.68% for JP-8.

e. There was no clear statistical proof of the dependence of dry bay overpressure on fuel temperature (90°F vs 75°F) for either fuel although a trend was indicated for JP-4 to produce higher overpressures at 75°F than at 90°F. No trend was observed for JP-8 between these two fuel temperatures.

f. There was no clear statistical evidence of the dependence of dry bay overpressure on initial fuel tank pressure (20 psia vs 15 psia) for either fuel.

g. For the vapor shots with 10 pores per inch reticulated polyurethane foam in the fuel tank, severe foam burning damage occurred during all three JP-4 tests whereas little foam damage occurred during the three JP-8 tests. The foam was equally effective in preventing fuel tank overpressures with both fuels.

h. The general conclusion of the program was that JP-8 was less susceptible to fire and explosion induced by gunfire, and structural damage should be less when compared to JP-4.

3. PRELIMINARY INVESTIGATION OF FUEL TANK ULLAGE REACTIONS DURING HORIZONTAL GUNFIRE (REFERENCE 7)

This test effort was conducted at Wright-Patterson Air Force Base (WPAFB) by the Air Force Aero Propulsion Laboratory to explore the fire and explosion response of the ullage space of a 90 gallon tank when subjected to CAL .50 API horizontal gunfire. The program was broad in scope and involved 230 shots. Two results were observed during the program which must be considered as part of the JP-4 and JP-8 discussion. (1) A projectile impacting a fuel tank ullage (vapor space) containing an equilibrium, nonflammable, lean fuel-air mixture (JP-8) can generate a combustion overpressure. Additional fuel in the form of vapor or spray enters the ullage from the liquid surface as a direct result of the projectile impact, passage thus creating a flammable mixture. (2) Combustion transfer from one tank to a connected tank occurred more frequently with lean fuel-air ratios (JP-8) than with fuel-air mixtures associated with JP-4. (Tanks divided by 1/4 inch aluminum plate containing four 1-inch diameter holes.) When applying the above results to the vulnerability evaluation of JP-4 and JP-8, one must bear in mind that the reaction overpressures associated with JP-8 were in general lower than with JP-4, although JP-8 reactions occurred over a wider range of initial conditions. It is believed that the combustion transfer phenomenon is highly dependent on tank configuration and the results of this program were not directly applicable to an aircraft environment. In this test series the method used for connecting the two tanks was typical of integral wing tanks, whereas the threat (vapor impact) and the configuration of the tank were typical for a fuselage tank. The results therefore should serve only as a departure point for additional analysis. Also in this program a series of tests were conducted with JP-4 using two tanks connected externally. This was accomplished by a 1-inch diameter hose approximately 2 feet long. No flame propagation from the impacted tank to the connected tank was observed in any of the six tests.

In another investigation, (Reference 8) McDonnell Douglas conducted four tests (CAL .50 API) with JP-5 using a 1-inch diameter hose 6 feet long to interconnect two tanks. Again no combustion transfer was observed. These two results tend to indicate for a 1-inch diameter hose externally connecting two tanks, combustion transfer may not be a problem for either high or low volatility fuels.

In summary, the bulk of the testing was conducted at equilibrium initial conditions. If equilibrium conditions could be relied upon in an aircraft fuel tank the comparison of the two fuels is mostly a question of knowledge of fuel tank temperature probability. Since an aircraft fuel tank is in a high nonequilibrium state, additional considerations are required. Projectile dynamics, fuel slosh, and vibration tend to make an initially lean ullage flammable, whereas fuel tank venting tends to render an initially rich ullage flammable. The combined effect of these opposing factors has never been investigated together in a single test program.

4. EFFECTS OF FUEL SLOSH AND VIBRATION ON THE FLAMMABILITY HAZARDS OF HYDROCARBON TURBINE FUELS WITHIN AIRCRAFT FUEL TANKS (REFERENCE 9)

This effort conducted by the Air Force Aero Propulsion Laboratory, using spark ignition, illustrated that fuel sloshing lowered the lean flammable limit in much the same way as the gunfire did in the previously described program. In the program it was shown that with sloshing fuel there was no distinct lean temperature limit at which the ullage gases change from flammable to nonflammable as there is under equilibrium conditions.

To illustrate the lowering of the lean limit for JP-8, a slosh frequency near fuel-tank resonance (~17 cycles per minute and 30° Double Amplitude) was selected and the results are shown on Figure 1. The reaction overpressures below the equilibrium lean temperature limit for JP-8 were comparable to the gunfire test results where the projectile generated a fuel spray. As expected, the rich flammable limit for JP-4 was not affected by the sloshing action. The vibration levels (500, 1100, 1200, 2000, 2500 and 3100 cpm and 0.050 inch double amplitude) also used in the test program did not produce sufficient agitation to effect the lean limit. For comparison, Reference 4 gives the typical wing vibration spectrum for the following aircraft.

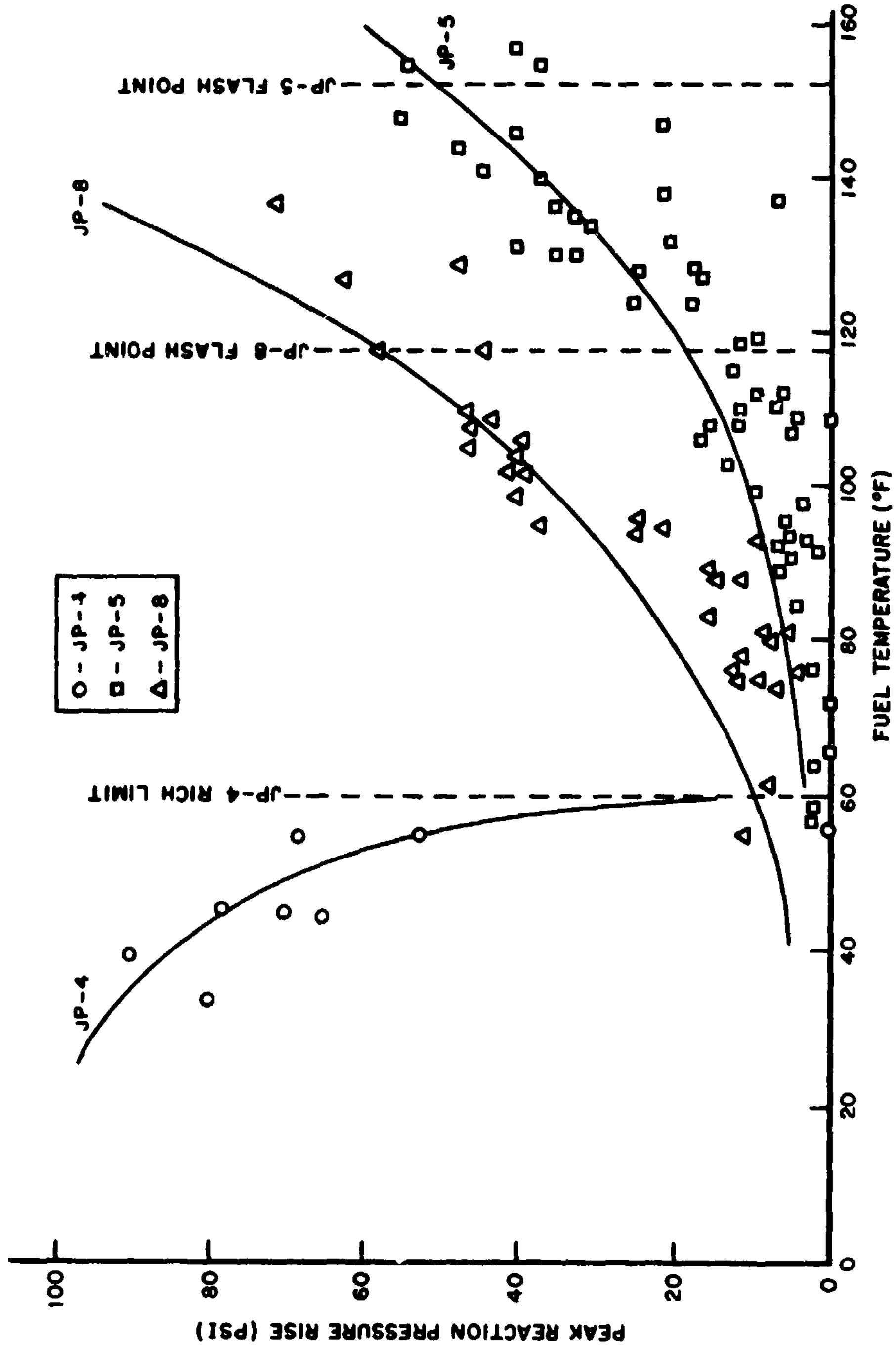

Figure 1. Extended Lean Flammability

Aircraft	Frequency (cpm)	Double Amplitude-Inches
F-100	30 to 840	0.1
F-106	30 to 600	0.08
B-58	30 to 42	0.3

Although there is insufficient test data and only limited information on the actual amount of fuel agitation experienced in the fuel tanks of operational aircraft, the problem of lowering the lean limit due to fuel agitation may not be as serious as originally expected and may not be a problem at all except during low altitude turbulent flight.

5. VULNERABILITY ASSESSMENT OF JP-4 AND JP-8 UNDER VERTICAL GUNFIRE IMPACT CONDITIONS (REFERENCE 10)

The first known effort involving vertical gunfire was initiated by the Air Force Aero Propulsion Laboratory in 1970. The principal objective of the program was to assess the relative vulnerability of JP-4 and JP-8 when impacted vertically (60° pitch-up) by CAL .50 API gunfire. The test program included 629 shots and was carried out in two phases: (1) non-equilibrium test conducted with a cylindrical tank to determine effects of fuel temperature, initial ullage pressure, tank volume, fuel depth, venting, etc. and (2) equilibrium tests conducted with various rectangular tank configurations to determine effects of initial fuel-air mass ratio of the ullage on ignition and reaction overpressures. Results of non-equilibrium tests (Phase I) showed that both JP-4 and JP-8 can be ignited over the temperature range of 10 to 130°F. Results also showed that reaction overpressures resulting from JP-4 tests were generally higher than those from JP-8 tests (see Figure 2). Increasing fuel depth and venting area tend to decrease reaction overpressures for both fuels.

Inspection of Figure 2 shows that the equilibrium rich temperature limit for JP-4 ($\simeq$60°F) and the equilibrium lean temperature limit for JP-8 ($\simeq$105°F) were significantly extended. In tests conducted with JP-8, ignition was observed at fuel temperatures as low as 10°F. At this temperature, the ullage equilibrium fuel-air mass ratio of JP-8 is in the order of 0.001 which is approximately one-thirtieth of that corresponding

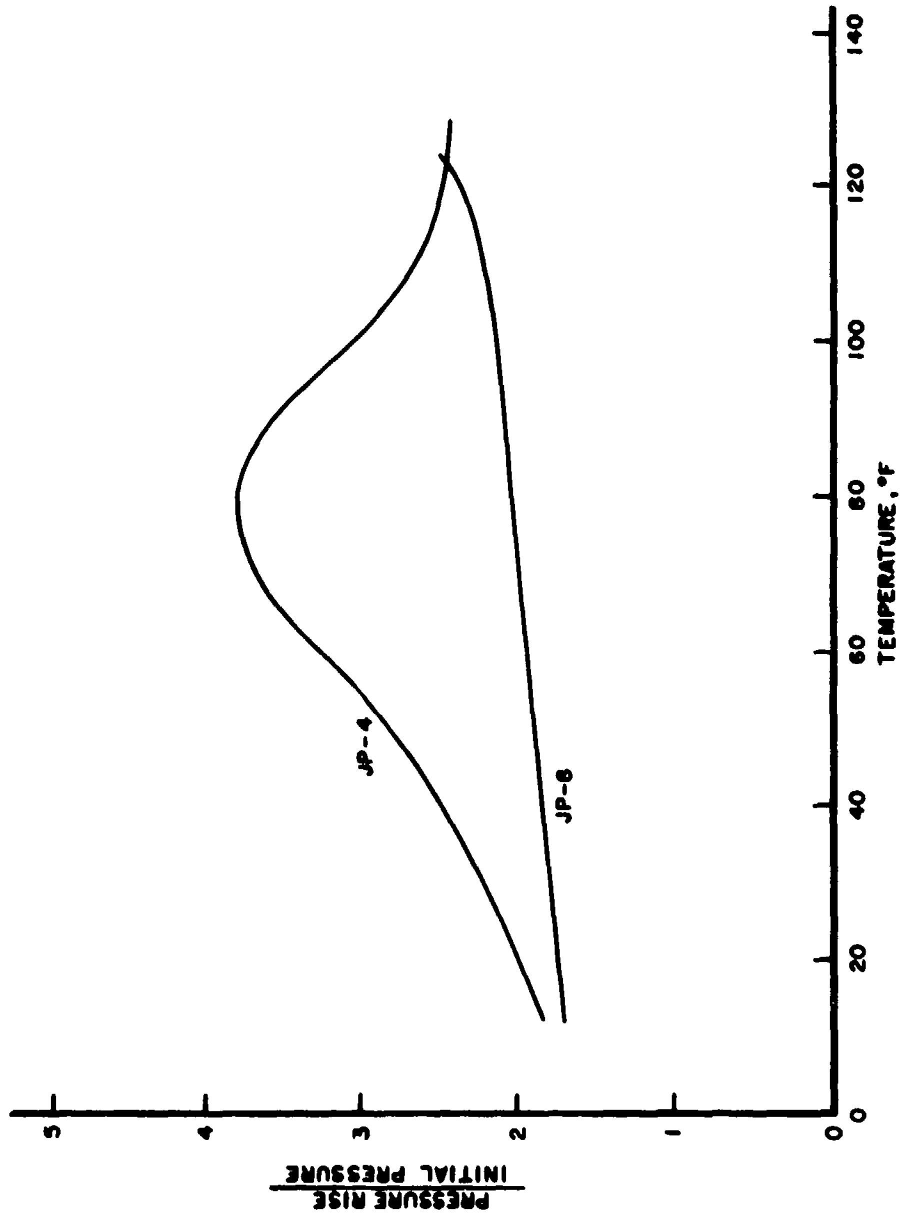

Figure 2. Effect of Fuel Temperature on Reaction Over-Pressure in Nonequilibrium Tests Conducted with JP-4 and JP-8, Four Inch Fuel Depth, and Atmospheric Ullage Pressure (90 Gal. Tank)

to the flash point temperature of JP-8. Thus the ignition observed at such low temperature represents a significant extension of the lean temperature limit of flammability. Analysis of high-speed motion picture film clearly indicates that such extension is due primarily to the impact-produced fuel mists and sprays.

In tests conducted with JP-4, ignition was observed at test temperatures as high as 130°F. This apparent extension of the rich limit of flammability however, should not be considered as a gunfire impact effect, for this extension is due mainly to the nonequilibrium fuel-air mixture conditions of the ullage. The waiting period between the time the tank and fuel temperature was stabilized at the desired test value and projectile activation was 20 to 30 minutes. This time was less than the time necessary to achieve equilibrium. This is evidenced by the ignition observed at the fuel temperature of 130°F which is well above the equilibrium rich temperature limit of flammability for JP-4.

The equilibrium tests (Phase 2) again illustrated, as discussed previously, that projectile dynamics generate fuel spray and cause an initially lean JP-8 ullage to become flammable. During the equilibrium tests with JP-4 the observed rich limit was less than the equilibrium rich limit due to enrichment of the ullage caused by the projectile generated fuel spray.

A total of eight tests, four with each fuel, were conducted to determine the effects of the Russian 14.5-113.8mm API. These limited tests indicated that there was no significant difference in the results between the CAL .50 API and the 14.5 API.

In conclusion, the results are shown on Figure 2 are typical of what to expect in an aircraft fuel tank when subjected to .50 caliber vertical gunfire.

6. OTHER RELATED GUNFIRE TEST PROGRAMS

McDonnell Douglas conducted a series of CAL. 50 API horizontal gunfire tests for the Navy (Reference 11) with the following results:

"Incendiary shots fired into the ullage space of 55 gallon drums containing JP-4 fuel produced bursting of the drums, whereas with JP-5 fuel, the ullage fires experienced were of low enough intensity to be retained by the drum structure. Ullage fires in the fuselage (cube) tank filled with JP-5 and high ullage volume, did not produce tank overpressures in excess of 8 psig."

Although the Douglas effort was wide in scope and there is some reason to question the statistical validity of the results, the result tends to support that argument that low volatility fuels are in general safer than high volatility fuels at fuel temperatures most generally experienced in aircraft and ground operations.

7. DAMAGE POTENTIAL

The foregoing test efforts provided information on two factors related to aircraft survivability, sustained fires and overpressure. Sustained fires can lead to structural failure and aircraft loss. This type of kill may require several minutes. The second factor is overpressure, either internal or external to the fuel tank. If the overpressure is sufficient to cause catastrophic structural failure the kill is immediate. If the structural damage is minor, there still is a high probability of a sustained fire kill. In any case, the mission and aircraft are generally lost. However, the pilot may survive a kill requiring several minutes.

The test programs clearly illustrated that JP-8 was less susceptible to sustained fires than JP-4. The question remains of how to compare the overpressure information when both fuels produce some level of overpressure. If the design specification overpressure for a fuel tank, generally 10-15 psi, is used as the acceptance criteria we see that in most cases both fuels produce overpressures above the design value. If we then assume a catastrophic structural failure occurs at the design value there is little difference between the two fuels.

To illustrate the point that the fuel system specification design overpressures can be of little value in assessing damage potential, AFAPL conducted a short test effort using an F-89J nose tank. The tank was subjected to a static pressure of 15 psig and various pulse overpressures (produced by spark ignition of propane-air mixtures) similar to those obtained by CAL .50 API gunfire ignition of fuel vapors. The following peak pulse pressures were obtained: 7, 9, 10, 15, 16, 19, 22, 26, 28, 41 and 49 psig. The tank suffered slight structural damage (four sheared rivets) at 41 psig. Catastrophic failure occurred on the next test at 49 psig.

This tank, a nonpressurized bladder type fuel cell, was designed to operate at 1.5 psig and, if aircraft fuel system design criteria were applied failure would be expected at about 10 psig static pressure.

This effort demonstrated that at least some fuel tanks have much higher static overpressure capability than expected based on the fuel system requirements. This is because in many cases the structural design requirements associated with aerodynamic loading and other factors not related to the fuel system are more severe than the fuel system design requirements. It is also important to note that pulse pressure maxima cannot be equated to static pressure information when assessing fuel tank damage potential. It should be noted that the failure characteristics for almost all fuel tanks when subjected to a pulse overpressure are unknown.

With the foregoing thoughts in mind and since a wide range of aircraft, each having several different types of fuel tanks with each tank having individual failure characteristics, it appears wise to assume that the degree of damage (no damage to minor damage to catastrophic failure) is a continuous function of overpressure since the force acting on a surface tending to produce failure is proportional to the overpressure. Now, any significant difference in overpressure between the two fuels is at least a subjective measure of the expected difference in fuel tank damage and therefore aircraft losses. The test programs clearly illustrated that

JP-4 tended to produce higher overpressures than JP-8, thus the number of aircraft immediate "kills" should be less with JP-8 when operating in environmental conditions similar to the test conditions.

The foregoing test programs represent a reasonable cross section of conditions possible on board an aircraft and the test procedures minimized the chances for experimental error. The threats used were small arms due to the importance of this size threats in the recent SEA conflict and the complications associated with testing at higher threat levels. For a given amount of effort, testing at the higher threat levels has a higher chance for experimental error and therefore a low confidence in the results. It is the opinion of the AD HOC Group that fuel type is unimportant for direct high threat AAA interactions with unprotected fuel tanks. High velocity missile fragments are in many cases similar to small arms where fuel type is important.

SECTION V

EFFECT OF FUEL IN AIRCRAFT CRASH FIRES

A recent survey was conducted to determine the statistical relationship between the occurrence of fire in a crash and the type of fuel used for turbine-powered aircraft. This survey includes worldwide civil aircraft accidents and noncombat military aircraft accidents. Accidents are included where the aircraft appeared to have impacted the ground or obstacles sufficiently hard to cause possible fuel spillage and fire after the crash. Examples of the types of impacts included are hard landings, wheels-up landings, contact with an obstruction, landing off runway, gear collapse, and striking terrain, mountains, or objects on the ground. Structural failures which could result in severing or piercing fuel lines and tanks were also included. The survey was limited to fixed-wing, turbine powered aircraft and contains no in-flight-fire cases. Data was obtained from World Airline Accident Summary, FAA, National Transportation Safety Board (NTSB) Accident Records, various air carriers for civil aircraft, U. S. Army Agency for Aviation Safety, the Naval Safety Center, and the Directorate of Aerospace Safety USAF for military aircraft.

The survey of worldwide civil airplane accidents which occurred during the time period from October 1952 to August 1972 shows that kerosene type turbine engine fuel is less likely to become ignited in an accident than JP-4 and, thereby, confirms the results of earlier laboratory tests in which the ignition and burning characteristics of kerosene fuel and JP-4 fuel were determined under controlled conditions simulating the circumstances of airplane accidents. (See Section VI). Of the 721 civil airplane accidents surveyed, complete fuel-fire information was obtained on 535 of the cases. Data on U.S. military noncombat aircraft accidents includes 19 U.S. Army accidents for a period July 1970 through September 1972, 173 U.S. Navy accidents for 1969, 1970, and 1971, and 151 USAF accidents for a period January 1965 through June 1972. Results are tabulated below:

TABLE X

FUEL EFFECT IN CRASH FIRES

	Type Fuel	Total Nr. of Cases / Nr. of Cases Involving Fire	% Post-Crash Fire (Rounded off to nearest whole number)
Civil	Kerosene JP-4	467/160 68/33	34% 49%
U.S. Army	JP-4	19/4	21%
U.S. Navy	JP-5	173/60	35%
USAF	JP-4	151/125	83%

The conclusions of this survey are as follows:

a. The theoretical safety advantage of a low volatility fuel in a crash situation is confirmed by this survey. Fire in a crash is less likely to occur with kerosene type fuel than with JP-4 type fuel.

b. Although exclusive use of kerosene type fuels in turbine-powered aircraft will not eliminate post-crash fires, it would substantially reduce the rate of occurrence.

c. The statistical evidence from the accident records confirms research laboratory results indicating the higher probability of ignition and fire in noncombat aircraft accidents when JP-4 is used.

It should be noted that the foregoing information on crash fires is being reassessed by a task force of the Coordinating Research Council. Preliminary results of this refined analysis indicate only 12% fewer crash fires with kerosene compared to JP-4. A Coordinating Research Council report on this subject is expected in 1976.

SECTION VI

TESTS BY OTHER AGENCIES ON NEAT AND MODIFIED JET FUELS

The U.S. Army, Naval Research Laboratories, and Federal Aviation Agency have conducted or sponsored tests in the area of fuel fire hazards such as those which can occur in flight, during servicing, and in a crash situation. Tests involving modified fuels, consisting of adding gelling or anti-misting agents to the base fuel, have been directed towards the control of fires in a crash situation but there has also been considerable data generated on the base fuels, either JP-4 or JP-8. Since a majority of the "fire tests" developed by agencies involved in the area were looking at the "worst case" condition, i.e., a severe ignition source, the first observation may be that all fuels are equally hazardous. However, analysis of the data, with respect to conditions that are representative of those which can exist in the fuel system, indicates that JP-8 has certain advantages over JP-4. In the assessment of this data, one must evaluate two basic parameters (1) the ignition source as it relates to the fuels and (2) the subsequent build-up of the fire.

1. IGNITION CHARACTERISTICS

(U) The basic volatility characteristics of the fuel and the ignition sources available from natural hazards in the aircraft such as electrical sparks or hot surfaces tend to favor the lower volatility JP-8 in lieu of JP-4. Over the operational temperatures normally encountered in fuel systems, the leakage of JP-4 would result in flammable vapors in areas surrounding the tanks and low energy ignition sources could readily ignite the fuel. Under similar conditions with JP-8 there are no vapors within the flammable range. In order to have a fire the ignition source must have sufficient energy to vaporize JP-8, thus shifting the mixture into the flammable range.

Many ignition sources typically found in aircraft do not possess enough energy to do this.

Several fire tests conducted by various investigators are given in Table XI.

The U.S. Army fire tests (Item 2, Table XI) simulating a post-crash condition which included sparks and hot surfaces as the ignition sources, indicated that JP-8 was less hazardous than JP-4 under these conditions. Work by the Naval Air Propulsion Test Center (NAPTC) (Item 3, Table XI) which evaluated the induction period for a fuel to ignite, also enforces the effects of vapor pressure/flammability zone on the fire hazard. In these tests, the time for ignition was studied as a function of fuel temperature and flash point. Relating the results to JP-4, one would conclude JP-4 could be a hazard above -10°F while JP-8 would not be a hazard until the fuel temperatures were near the flash point range of 105 to 150°F.

The FAA (Item 9, Table XI) conducted a series of tests where an external drop tank was dragged across concrete containing a series of steel spikes. The objective was to determine the ignition characteristics of dispersed fuel when a tank ruptures. The ignition source was an electrical arc attached to bottom side of the tank. Tests with JP-4 resulted in ignition and propagation of the flame over the entire trailing path of fuel while with JP-8 fuel ignition was noticed but flame did not propagate. It was estimated that only 1.0% fuel involvement with JP-8 occurred as compared to total involvement with JP-4.

2. BUILD-UP OF THE FIRE

The involvement of the fire, once ignition occurs, is the second parameter to consider in evaluating the fire hazard of the fuels. This is related to the flame spread rates (Reference 12, Item 1, Table XI) of the fuels -- 7.3 ft/sec for JP-4 and 0.01 ft/sec for JP-8 -- when measured in a V-shaped metal trough (3 inch angle iron) four feet long. This difference in the time for total involvement of the fuel has been studied by several investigators as shown in Table XI. The tests associated with the impact dispersion or open burning, such as those developed by the Bureau of Mines or the Army (Item 4, Table XI) are similar. Here, the

TABLE XI

SUMMARY OF FIRE TESTS

DESCRIPTION	AGENCY	IGNITION SOURCE	RATING OF FUELS		REMARKS
			JP-4	JP-8	
1. Flame Spread (Reference 12)	Bureau of Mines	Open Flame	7.3 ft/sec	<0.01 ft/sec	
2. Post-crash - Surface (Reference 13)	U.S.A.	Hot Surface	Hazardous	Nonhazardous	
Post-crash - Engine	U.S.A.	Spark	Hazardous	Nonhazardous	
Post-crash - Open Flame	U.S.A.	Open Flame	Hazardous	Hazardous	
3. Ignitability/Induction Time (Reference 14)	NAPTC	Wick	Immediate	Delayed Ignition	
4. Open Burning (Reference 15)	U.S.A.	Open Flame	0.3 sec	>90 sec	Difference dec. @ higher temp (>100°F)
5. Impact Dispersion	U.S.A.	Open Flame	Very High	High	Transient fire ball with JP-4 violent
6. Mist Flashback	U.S.A.	Open Flame	Very High	High	
7. Air Gun (Reference 16)	FAA	Open Flame	16 Btu/ft^2/sec	13 Btu/ft^{2}sec	Radiant energy from fire
8. Catapult Test	FAA	Open Flame	4.7 Btu/ft^2/sec	3.8 Btu/ft^2/sec	Radiant energy from fire
9. Drag Test	FAA	Spark	100% Ignition	1.0% Ignition	Leaves "trail" of fuel, ignition at source of leak

NOTE: In test where the ignition source is an open flame the fuel is expected to burn.

periphery of the test area contains open flames and the size of the fire ball or time for total involvement of the fuel is measured. With JP-4, reactions are immediate and somewhat violent (explosions) while time for involvement of JP-8 is considerably longer. For instance, the time for open burning of JP-4 at 70°F (trough 46 cm x 3.8 cm x 0.48 cm) was less than 0.3 seconds while for JP-8 the time was in excess of 90 seconds. Also with the reduced vapors as ociated with JP-8 at the test temperatures (<100°F) the ignition of the mists, if any, was less violent than that noted for JP-4. This pool burning effect as noted in these ambient tests could also be applied to fuel systems or servicing conditions. Under these conditions, one could expect that there would be total involvement of JP-4 almost immediately, while the time for JP-8 would appear to offer some additional advantage.

3. MODIFIED FUELS

The relative ease with which JP-4 vaporizes and the rapid flame propagation rates indicates that there is little one can do to increase its safety. However, as evidenced by the strong interest in modified kerosene base fuels, the reduced volatility and flame spread rates of JP-8 can lead to a safer fuel. Most of the fire tests developed for evaluation of these fuels are representative of the crash situation and tend to create the "worst case" condition, that is, a mixture of fuel mists and open flames, thus the expected result is a fire. Results of the gels or anti-mist fuels show that there is a marked reduction in the fire hazard. For example, the mist flashback apparatus developed by Southwest Research Institute (SwRI) for the Army (Item 6, Table XI) subjects the fuel to a low shear rate which creates a mist of fuel similar to that expected in a crash condition. This mist is sprayed through a flame zone and the tendency for the flame to transverse back to the nozzle area is measured. Conventional fuels have a high rating while modified fuels do not flash back, hence a low rating. Data from the FAA (Item 7, Table XI) with the air gun also show improvement with modified fuels. Here, the fuel is shot through a grid and behind the grid is a series of open flames. Total involvement of the fuel is the parameter measured.

Full scale crash tests conducted by the FAA also indicate that modified kerosene offers significant improvement over conventional JP-8 when subjected to an open flame ignition source. In order to assess the potential of anti-misting fuels under gunfire conditions, the Air Force Aero Propulsion Laboratory recently completed a test program similar to the one described in Section IV, Part 5. The neat JP-4 had an average pressure rise of 47.9 psi and neat JP-8 had 32.9 psi. Comparing the two neat fuels, there was a significant statistical difference at the 95% confidence level. When 0.3% anti-misting additive was added to JP-8, the average pressure rise was 7.5 psi. When the same additive was tested with JP-4 the pressure rise was 54.0 psi. Although there are operational problems associated with the current additives the potential for additional combat benefits exists with JP-8 and not JP-4.

In conclusion, the data available from the foregoing fire tests indicates that the reduced volatility and flame propagation rates of JP-8 favor its usage over JP-4. In situations where fuel leakage or spills may occur such as those which can be encountered in fuel servicing operations, the low volatility of JP-8 would probably preclude formation of flammable vapors. Further, if a fire would occur, time for appropriate action, that is extinguishment or evacuation of the area, could be of significant advantage with JP-8 in lieu of JP-4. In addition, the potential for increased combat benefits exists with JP-8 by the use of anti-misting additives.

SECTION VII

FLIGHT TEST EVALUATION OF JP-8 FUEL

1. FLIGHT TESTS WPAFB 1963

In-flight evaluation of a turbine engine fuel essentially the same as JP-8 was conducted in 1963, when TAC requested an evaluation of the effects of commercial Jet A-1 fuel on the performance of the F-100 aircraft. In several deployment locations Jet A-1 was the only readily available fuel. There was concern over the effect this fuel may have had on the aircraft's operational performance, especially above 30,000 feet.

A flight test (Reference 17) was performed at Wright-Patterson and Edwards Air Force Bases by ASD, using an F-100F aircraft. At that time Jet A-1 fuel had an allowable flash point range of 110-150°F, although the actual flash point of the test fuel was not reported. The report does state that one modification was made to the aircraft prior to the test: "During periodic inspection, an AA14S ignitor plug was removed and a JD-57 ignitor plug installed. The JD-57 is a long reach plug and has better relight characteristics than the short reach AA14S plug."

Airstart data obtained in the range of 35,000 to 40,000 feet altitude indicated that there was no degradation of the upper limit of the JP-4 airstart envelope when the aircraft was flown on Jet A-1 fuel. As a result of this testing, commercial fuel was designated for limited use with recommended substitution of a long reach ignitor.

2. FLIGHT TESTS WPAFB 1968

A short term "initial impact" type flight test program was conducted on JP-8 by ASD, WPAFB in 1968 (Reference 18). It involved the use of both JP-4 and JP-8 in typical SEA aircraft including the T-39, C-135, F-4C, B-57, T-38, and F-101B, as well as related ground support equipment. The evaluation testing included aerial relight, exhaust gas smoke emission, engine performance, ground starting characteristics and associated maintenance requirements. Although a significant amount of data was collected, the flight test was terminated when it became apparent that the impact of using JP-8 would require testing beyond the scope of the program.

Engine fuel controls were adjusted for the T-38 only; all other aircraft used normal JP-4 settings. There was no detectable effect on engine operation or on performance characteristics with the use of JP-8 as measured by normal checkout procedures. The data obtained during the test was insufficient to establish JP-8 relight envelopes for any of the aircraft.

In terms of aerial relight capability, all aircraft except the F-101 were tested with JP-4 and JP-8 fuels at points derived from the respective aircraft handbooks and relight envelopes. Normal shutdown times were intended to be representative of actual flight and combat conditions and, for each condition, extended cold soak (shutdown) times in the order of 10-15 minutes were also evaluated. Normal shutdown times ranged from 0.3 to 4 minutes duration. On all tests, even with extended cold soak times, no problems were encountered with JP-4 restarting. With the use of JP-8 fuel, having a flash point of 118°F, no significant relight degradation was noted on the T-39 (J-60-3A) and C-135 (J-57-P-59N); however, a significant degradation was found to exist on the F-4C (J-79-15), B-57 (J-65-5B) and T-38 (J-85-5). Results of the F-4 testing show that, for shutdown times of 1-4 minutes, a general reduction in relight altitude of 6,000 feet was realized. Relight data accumulated on the T-38 with control settings on JP-5 indicated a substantial drop in relight altitudes from 30,000 feet on JP-4 to 20,000 feet for JP-8 with shutdown times less than one minute. In the case where the shutdown times were extended to 5-10 minutes, relight could not be attained even at 20,000 feet. Airstart tests on the B-57 was limited to two airspeeds (175 and 220 kias) and one altitude (12,000 ft). The JP-8 airstarts could not be accomplished at the 220 kias point.

Ground start data was obtained in an ambient temperature range of 15° to 44°F. In general, cold weather ground starting with JP-8 was difficult with the T-38 and unacceptable with the F-101B. Satisfactory ground starts were obtained for the T-39, F-4C, and B-57, while no data was recorded for the C-135. Starts were reported for the F-4C at 44°F, the B-57 at 22° and the T-39 at 30°. The T-38 started four times and failed to start twice in a temperature range of 25° to 33°F. The F-101B started only once in eight attempts at 15° to 22°, and the one start was achieved with great difficulty. Because of this problem, no air-start data was obtained for the F-101B. Limited testing on the B-57, KC-135, T-38, and T-39 aircraft indicated that visible exhaust gas smoke emission was not appreciably increased on a short term usage basis.

3. FLIGHT TESTS EDWARDS AFB 1972 (REFERENCE 19)

In order to determine the entire F-4 airstart envelope for JP-8 fuel, a flight test program was initiated by AFAPL. The actual test began on 6 September 1972 at the Air Force Flight Test Center, Edwards AFB, California, using an F-4E aircraft and JP-8 fuel with a flash point of approximately 128°F. The basic procedure used to evaluate each airspeed altitude point was to shut down one engine, wait approximately 30 seconds and attempt a relight. It was felt by the test pilots involved that this was a reasonable amount of time; normal Tech Order procedure requires a routine systems inspection in the event of an engine failure, followed by an immediate airstart attempt. High speed airstarts were attempted after a shorter shutdown due to the inability of the aircraft to maintain speed and altitude on one engine. For each point evaluated, airstarts were attempted first on one engine and then the other.

Starting 6 September 1972, the JP-4 envelope was confirmed by testing several points on the edge of the envelope using JP-4 fuel. The JP-8 testing began on 6 October 1972. The main fuel control units on the engines were adjusted to the JP-5 setting for these tests.

The only degradation in airstart capability noted for the points tested was an increase in airstart times. Refer to Figures 3 and 4 for points tested. Compared to baseline JP-4 airstarts, JP-8 airstarts required 10 to 25 seconds longer from ignition/throttle ON to idle rpm. Most of the JP-8 airstart times did not exceed 45 seconds and were considered operationally acceptable. One airstart took 64.6 seconds, which was considered excessive. Data was not obtained above 50,000 feet and Mach 1.6.

Throttle transients (IDLE to AFTERBURNER) were conducted to investigate engine stall susceptibility up to 48,000 feet and 24 units angle-of-attack. A baseline was established with JP-4 fuel to determine maneuver and throttle transient conditions where compressor stalls and flameouts were experienced. Similar conditions were then flown with the JP-8 (and with JP-5), up to the boundary conditions experienced with JP-4. Test results demonstrated that there was no loss in afterburner light-off nor any increase in susceptibility to engine compressor stall or flameout during throttle transients associated with the use of JP-8 fuel.

The final phase of testing began 1 November 1972 when the aircraft was serviced with JP-5 and the airstart envelope evaluated for this fuel. Results were similar to those obtained with JP-8 except that five unsatisfactory starts occurred in the 25,000-30,000 feet altitude/Mach 0.40-0.45 region, which is the region where one excessive time to idle start with JP-8 was experienced. The test agency considered this data sufficient justification for limiting the maximum flash point of JP-8 fuel to 140°F in lieu of 150°F.

Because of instrumentation requirements, the aircraft was normally stored in a hangar overnight. When the aircraft, serviced with JP-5, was left outside one night and started the next morning after an early morning low of 30°F, billowing white smoke was observed which was judged excessive and the start was aborted. EGT and RPM were slowly increasing when the start was aborted. A start attempt on the other engine yielded the same results. Visual inspection revealed that the afterburner was

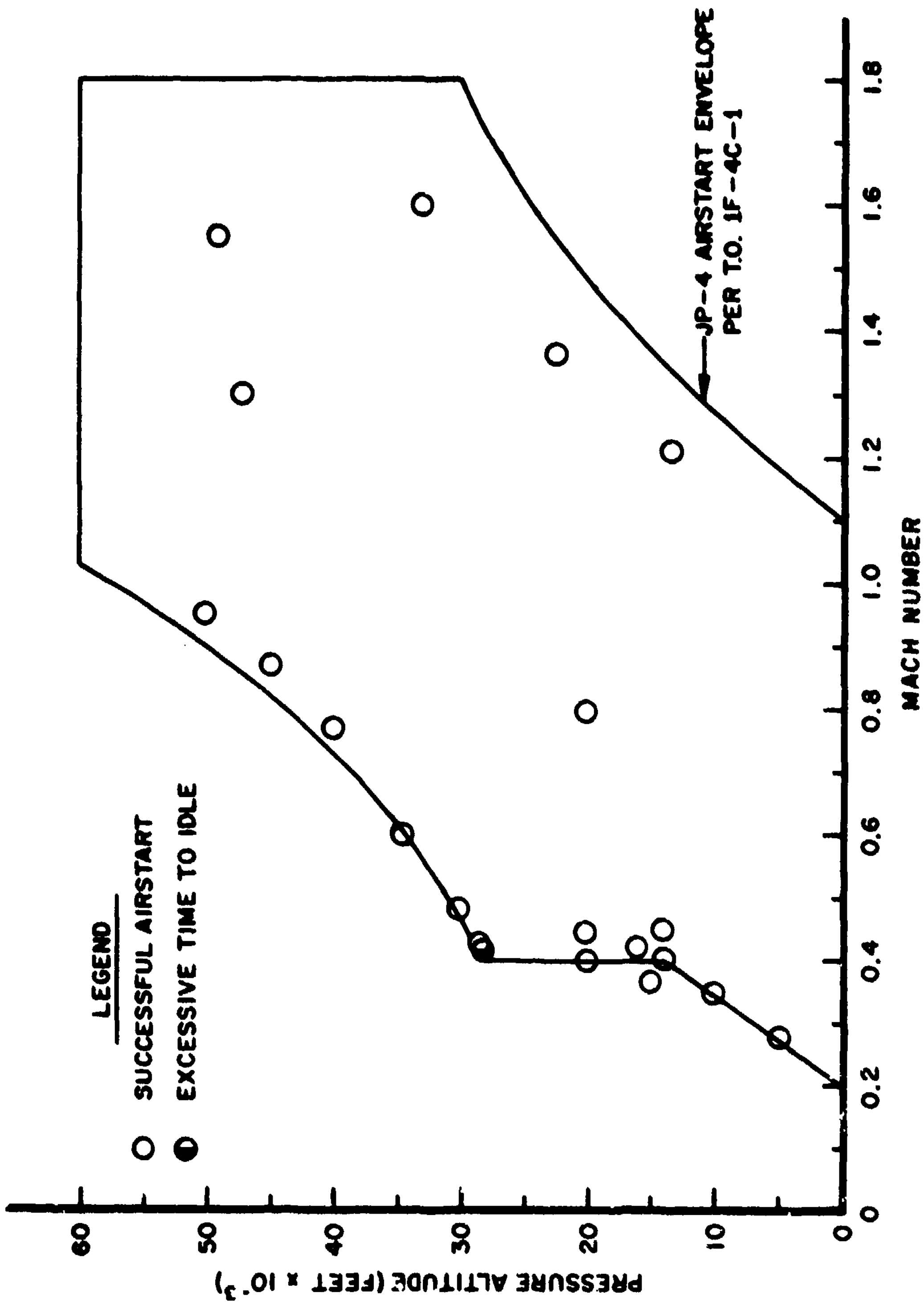

Figure 3. JP-8 Airstarts (Right Engine)

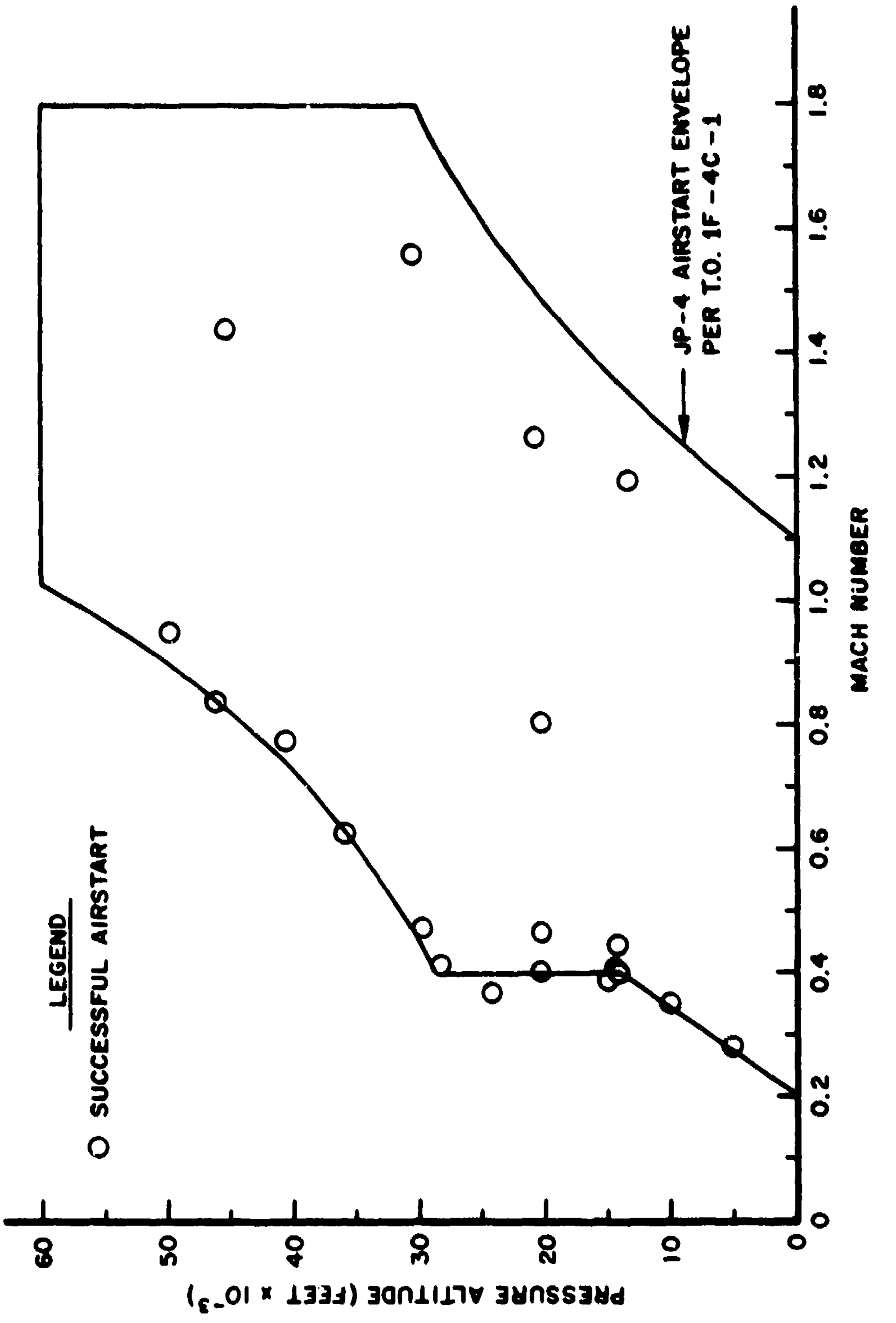

Figure 4. JP-8 Airstarts (Left Engine)

soaked with fuel. It was reasoned that although light-off had occurred, flame propagation within the combustor had not proceeded normally.

The above start procedure was tried with JP-8 after a minimum air temperature of 32°F. Billowing white smoke again occurred but cleared up after several seconds of operation. The second engine was started with the same results. This type of start characteristic was judged to occur with low volatility fuels when the aircraft fuel temperature is 50°F or below. These occurrences were the basis for the test agency recommending detailed cold temperature start testing before general usage of JP-8 by the Air Force.

4. ANALYSIS

Due to the significantly lower vapor pressure of JP-8 fuel as compared with JP-4, some reduction in the F-4 airstart envelope was anticipated. In the recent F-4E flight test, the effect was more in the direction of extending start time than reducing light-off limits. In the previous tests at ASD a difference in airstart envelope was noted. Several explanations for the difference between the WPAFB and AFFTC F-4 data are the difference in engines (J79-15 vs J79-17), shutdown times were longer for the WPAFB test, and the fuel control was set for JP-4 for the WPAFB test whereas it was set for JP-5 for the AFFTC test. Hence, soak time prior to relight appears to be more critical with low vapor pressure fuel.

5. FLIGHT TEST CONCLUSIONS

Results of flight tests thus far have been inconclusive. The depth of testing, modification work, maintenance manual changes, and associated activity that would be involved in an Air Force changeover to JP-8 fuel must still be completely determined. The F-100, C-135, T-39, and F-4E tests showed a general similarity in relight envelope and flight performance whereas the 1968 WPAFB tests showed that on the F-4C, B-57, and the T-38 air relight characteristics are substantially different between the two types of fuels. The WPAFB and the F-4E tests showed that ground start characteristics need to be thoroughly evaluated and the necessary capability developed before a changeover in fuel is accomplished.

SECTION VIII

IMPACT OF JP-8 ON FUEL SYSTEMS AND AIRCRAFT PERFORMANCE

1. GENERAL

There is a minimum impact on airframe fuel systems by switching from the current JP-4 fuel to the proposed JP-8 fuel. Many of the current airframe systems can satisfactorily use either JP-4 or JP-5 fuel and since JP-8 has characteristics between these two fuels no major problem is foreseen. Since JP-8 is not a viable alternative to current inerting systems, the need for polyurethane foam and nitrogen fuel tank inerting systems is not expected to change. Engine fuel systems may require test and/or modifications.

Aerial refueling operations are expected to be significantly affected due to potential fuel freezing in the boom and decreased flow rate due to the increased viscosity of JP-8. A comprehensive flight test program is recommended.

The 1968 WPAFB tests indicated that several systems will experience ground and flight starting difficulties upon introduction to JP-8 fuel. These difficulties increase in severity as ambient temperatures are reduced. Some engines will require modification whereas others will require only adjustments or procedural changes.

Evaluation will be needed under some of the component improvement programs and appropriate modifications accomplished. Some system ground and flight tests will be needed, particularly under adverse environmental conditions, to establish operational limits.

2. EVAPORATION AND ENTRAINMENT LOSSES DURING CLIMB TO ALTITUDE

Fuel boils when ambient pressure at the liquid surface falls below fuel vapor pressure. The vapor pressure of JP-8 fuel is about 1/25 of that for JP-4 at 100°F. Quantitatively, this advantage can be expressed in terms of the altitude at which boiling occurs without tank pressurization. This is 81,000 feet for JP-8 versus 35,000 feet for JP-4. Use of JP-8 in current systems would prevent boil-off losses when tank pressurization is lost due to ordnance damage or system malfunctions. Also, current pressure levels are not high enough to entirely suppress all evaporation losses with JP-4 in some current aircraft whereas no losses would occur with JP-8. The effect of JP-8 on future system design would be to reduce or eliminate the need for fuel tank pressurization and could reduce the size of the dewar if a nitrogen inerting system is to be part of the design.

Entrainment losses (losses of liquid fuel during venting) are not expected to differ greatly between the two fuels. These losses may actually be slightly less with JP-8 since the air solubility in JP-8 is .0073 volume air/volume liquid compared to .011 for JP-4.

3. HEAT SINK/HEAT TRANSFER

There is a definite trend in modern high performance aircraft to use the fuel as a primary heat sink for cooling generator, avionics, hydraulic equipment and subsystems. This increases bulk fuel temperature in main tanks to the 180-250°F range for some systems under development, which is well above the normal design fuel temperature range of current systems (135°F maximum). The result is airframe fuel system design complications due to the vapor pressure of JP-4 at these elevated temperatures (Table XII). Utilizing the heat sink at the higher temperatures requires addition of emergency pumps in the tanks as back-up for the boost-pump-out condition, increased fuel tank pressurization levels, unconventional fuel cooling techniques such as pumping heated fuel into wing tanks and use of larger capacity pumps to compensate for the higher vapor pressure at these temperatures.

Use of JP-8 would not have much impact on current aircraft from the standpoint of heat sink requirements. For aircraft under development heat sink-vapor pressure problems have been resolved by minor systems changes/rearrangements as discussed above. Future high performance aircraft and growth versions of high performance aircraft under development most likely will require additional heat sink, further complicating

TABLE XII

VAPOR PRESSURE OF JP-4 AND JP-8

Temperature - °F	Vapor pressure - psia	
	JP-4	JP-8
100	2.8	0.1
135	5.3	0.2
200	12.5	0.9
250	25.0	2.5
300	39.0	5.0

airframe fuel system design or forcing a change to lower volatility fuel. Note that to obtain this additional heat sink in the airframe (low pressure fuel system) an increase in thermal stability to provide the required heat sink in the engines (high pressure fuel system) is necessary regardless of fuel type. There is no particular advantage of JP-8 over JP-4 as each can be processed to give the same level of thermal stability and thus the same total heat sink. The advantage of JP-8 is design flexibility.

Heat transfer will not differ substantially for JP-4 and JP-8. Table XIII indicates that the transport properties of JP-4 and JP-8 are practically equivalent above 100°F.

4. LOW TEMPERATURE OPERATION AND FUEL FREEZING

The specified maximum freezing points for JP-4 and JP-8 are, respectively, -72°F and -58°F. The impact of JP-8 usage has been evaluated in terms of the ambient temperatures at which current aircraft can operate without incurring fuel freezing problems.

TABLE XIII

TRANSPORT PROPERTIES OF JP-4 AND JP-8

Property	Units	Fuel	Temperature - °F		
			100	200	300
Density	lbs/ft^3	JP-4	46.48	43.80	41.18
		JP-8	49.60	47.04	44.48
Viscosity	centistokes	JP-4	1.00	0.62	0.45
		JP-8	1.50	0.78	0.52
Specific heat	Btu/lb °F	JP-4	0.51	0.56	0.62
		JP-8	0.49	0.55	0.60
Thermal conductivity	Btu/ft/ft^2 hr °F	JP-4	0.079	0.076	0.074
		JP-8	0.078	0.074	0.069
Enthalpy (Sat. Liq.)	Btu/lb	JP-4	45	97	153
		JP-8	40	92	147

The impact on flight operations is unresolved. Flight testing of 707, RB-57F, B-52, KC-135, and C-141 aircraft indicate that bulk fuel temperature will reach stagnation temperature after about 3 hours flight time. It would appear that there will be no in-flight freezing problems with JP-8, based on stagnation temperature, since ambient temperatures which give stagnation temperatures below the freezing point of JP-8 are not commonly encountered. For instance, referring to Table XIV, at Mach 0.7, flight would have to occur at ambient of -95°F before the stagnation temperature would reach the JP-8 freezing point of -58°F. A -95°F ambient is observed for sustained periods only with special high altitude aircraft.

However, the stagnation point, i.e., at the leading edges, is not the coldest point on the aircraft skin. Recovery occurs so that minimum skin temperature falls somewhere between stagnation temperature and ambient temperature. A very conservative recovery factor of 0.5 has been applied to give results of Table XIV where recovery temperature is defined as coldest skin temperature. These calculated ambient temperatures based on recovery temperatures appear to be near what can be experienced with current aircraft such as the KC-135. It is believed that, with the

TABLE XIV

AMBIENT TEMPERATURES GIVING AIRCRAFT SKIN TEMPERATURE EQUAL TO FUEL FREEZING POINT

Mach Nr.	Ambient Temp. based on Stagnation Temp. °F.		Ambient Temp. based on Recovery Temp. °F.	
	JP-4	JP-8	JP-4	JP-8
0.2	-76	-62	-74	-60
0.3	-80	-66	-76	-62
0.4	-85	-71	-79	-65
0.5	-91	-78	-82	-68
0.6	-99	-86	-86	-72
0.7	-108	-95	-91	-78
0.8	-118	-105	-96	-83
0.9	<-120	-115	-101	-88
1.0	<-120	<-120	-107	-95

exception of certain circumstances (less than 3% of operations), there will be no freezing problems with JP-8 as actual recovery temperatures probably are near stagnation temperature. Selected flight tests (B-52, F-111 and KC-135) would be needed to completely determine the full impact of JP-8 at low temperature extremes.

Commercial operators have increased usage of Jet A fuel which has a -40°F freezing point. The motivation for using Jet A in lieu of Jet A-1 (-54°F freezing point) is the greater availability of Jet A. Flight paths are arranged to bypass regions where the -40°F freezing point would be a problem. The military does not have this flexibility.

Ground operations, with the exception of Antarctica, would not be subject to any fuel freezing problems with JP-8. Systems are supposed to be designed so that they are not affected by exposure to -65°F for 72 hours (Reference 20). Locations other than Antartica rarely experience this condition (Table XV). The large difference between the mean and the coldest temperature, indicated in Table XVII suggests that occurrence of the coldest temperature is infrequent.

TABLE XV

LOW TEMPERATURE EXTREMES

Base	Coldest Annual Temp., °F	Coldest Month Mean of Coldest Daily Temp., °F (Month)
Elmendorf, Alaska	-43	+5 (Jan)
Minot, North Dakota	-34	-3 (Jan)
Thule, Greenland	-44	-22 (Mar)
Loring, Maine	-30	+3 (Jan)
Goose, Newfoundland	-38	-6 (Jan)
Eielson, Alaska	-61	-20 (Jan)
Little America (Antarctica)	-78	-43 (Aug)
South Pole Station (Antarctica)	-107	-82 (Aug)
McMurdo Station (Antarctica)	-59	-28 (Aug)

Based on the above data, it is concluded that JP-8 will not freeze on the ground at most geographical locations.

Continued use of JP-4 for specialized aircraft or locations such as Antarctica can be considered in the event all other systems are converted to JP-8. This type of practice is performed routinely for the U-2 and SR-71 which require placement of special fuels but the quantity is low having no effect on other fueling operations.

5. FUEL LUBRICATION

A number of airframe and engine fuel system components including pumps, controls, and fuel driven hydraulic actuators are fuel lubricated. The lubrication characteristics (lubricity) of a fuel depends on the fuel viscosity and its chemical composition. On the basis that at room temperature the viscosity of JP-8 is higher than that of JP-4 and because the Navy and commercial airlines operating on JP-5 and JET A-1 have not reported any lubricity problems, it has been suggested in a previous study (Reference 21) to delete the MIL-I-25017 corrosion inhibitor additive from JP-8. It has been found that the additive has a major impact on lubricity with JP-4. In this study, however, it is concluded that the additive cannot be deleted from JP-8 at this time. This is due to the importance of fuel additives, aromatics, etc., on wear characteristics (Reference 22) and the variation in chemical composition that could be expected with production of JP-8. Also JP-4 and JP-8 viscosities are about the same at the higher temperatures (Table XIII) anticipated in systems under development. Therefore, there is little advantage of JP-8 over JP-4 with respect to lubricity and the use of corrosion inhibitor is still required to guarantee uniform lubricity.

6. AERIAL REFUELING SUBSYSTEMS

There could be a major impact on aerial refueling if JP-8 is adopted as the primary Air Force fuel. Since the freeze point of JP-8 is warmer than that of JP-4 (-58°F versus -72°F), there is a potential freezing problem of residual fuel trapped in the boom following a refueling operation. If fuel freezing is found by flight testing to be a problem then modification to eliminate or heat the residual fuel will be required. The problem may be aggravated with new multipoint refueling concepts since fuel dumping would not be possible with the hardware concepts now under consideration.

The other potential impact on aerial refueling operations with JP-8 is the anticipated decrease in flow rate and corresponding increase in refueling time due to the increase in fuel viscosity at temperatures below zero degrees (Refer to Table II, Section III). This will be evidenced on all receivers but primarily on those that are utilizing full tanker capability. B-52, C-5, EC-135 Command Post, B-1, and 747 Command Post aircraft will probably experience an increase of from 1 to 4 minutes for a nominal off-load. A comprehensive flight test program will be required to fully determine the impact of JP-8 on aerial refueling operations.

7. BOOST PUMP DESIGN

The impact of fuel properties on pump design depends on how a pump is driven, at what speed, the displacement mode, and method of coupling with other pumps.

Pump horsepower varies directly with the specific gravity and is influenced in a more complex manner by viscosity. In general, pump capacity is reduced with increasing viscosity, however, with JP-8, the increase in viscosity is not significant to pump capacity.

Delivery of 135-200°F JP-4 to engine pump boost stages is a current design requirement. Pumps are designed to deliver at 0.45 vapor-liquid ratio (V/L) which is now realistic with JP-4 at the cited temperatures. However, to meet this vapor condition, pump design is dramatically affected.

A recent case of interest involved redesign of an engine boost stage pump that was limited to 0.3 V/L at 135°F at 45 gpm and a 60 psi rise. The drive mode and speed were fixed. The redesign enlarged the inducer to give the same delivery at 0.45 V/L, with capability for higher temperatures, i.e. higher V/L. However, weight increased from 26 to 32 lbs and heat rejection tripled.

The use of JP-8 would tend to ease the vapor problem and thus allow for an easier engine boost pump design. This is illustrated in Figure 5 which shows a computer study of an engine feed system for an aircraft under development. Notice that JP-8 does greatly reduce the vapor problem at a given altitude. In terms of existing and future weapon systems, JP-8 will ease the V/L problem.

8. IMPACT ON AIRCRAFT INSTRUMENTATION

a. Rate of Fuel Flow Measurement

In the rate of fuel flow measurement area no significant problem will be experienced. Since current fuel flow transmitters use the angular momentum mass flow measuring technique they can easily measure JP-8

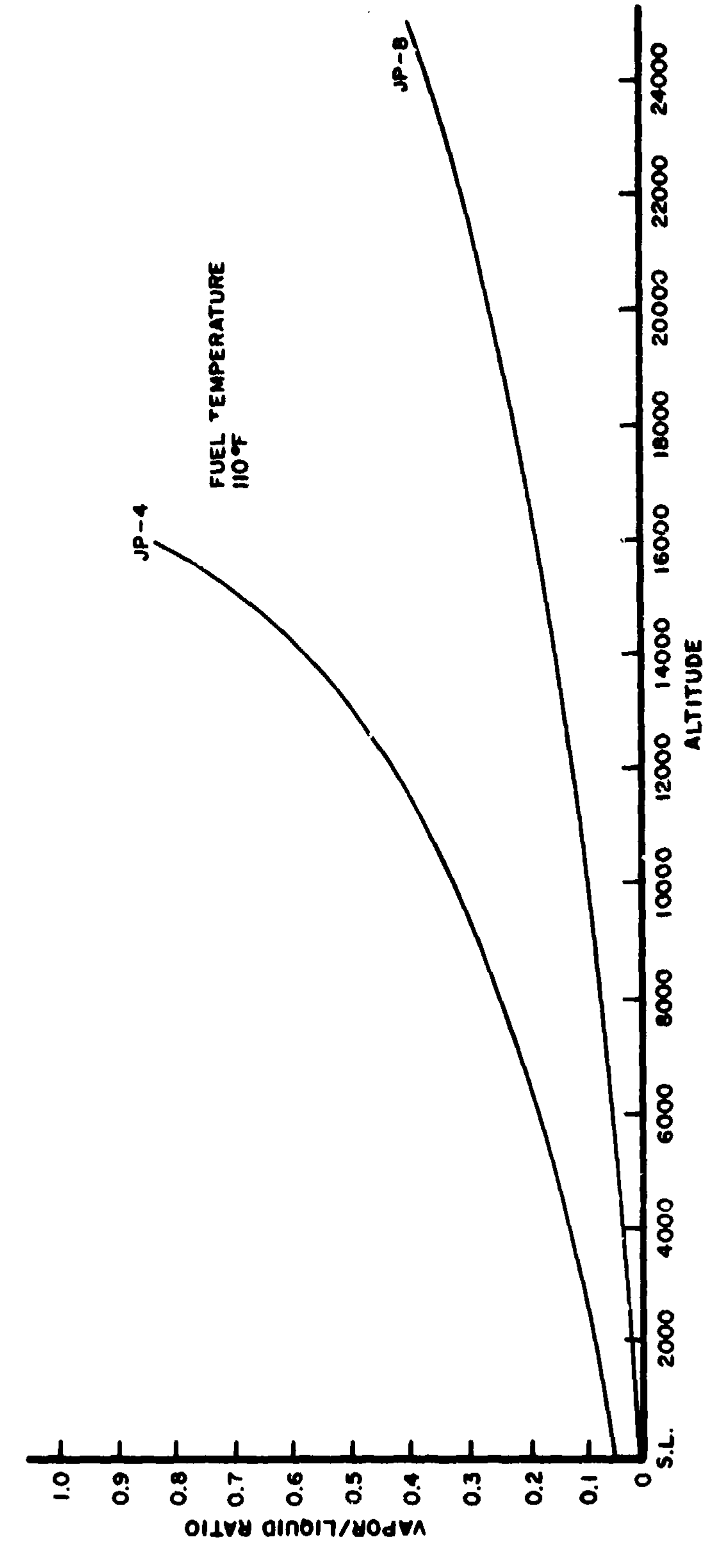

Figure 5. Effect of Fuel Type on V/L Ratio for Typical Fuel System

which has a slightly higher density than JP-4. The low temperature test temperature of -71°F will have to be raised since JP-8 typically freezes at -59°F.

b. Fuel Quantity Measurement

The measurement of fuel quantity will pose some problems, since the fuel quantity measurements are for the most part capacitance type gaging systems. The design of these systems is based upon the specified dielectric constant of JP-4 fuel. Since the dielectric constant of JP-8 is different than JP-4 a simple substitution of fuels would result in measurement errors unless the fuel measurement system is redesigned for JP-8 fuel. New fuel measurement systems such as used in the B-1, which utilize attitude correction and fuel management techniques could "design in" or "store" a second dielectric curve in the memory core of their attitude computer memory to cover both types of fuel. Other systems without attitude correction would probably need recharacterization of the capacitance probes used in the fuel tanks. The other option would be to accept the error caused by a change to JP-8. The exact amount of increased error cannot be computed, however, without detailed dielectric constants, at various temperature increments, from -94° to 158°F.

9. FUEL EFFECTS ON ENGINE STARTING AND OPERATION

a. Engine Operation

The wide commercial usage of kerosene type fuel and Navy usage of the heavier JP-5 fuel establishes a basis for Air Force operation with JP-8 fuel without significant effect over the normal range of operating conditions. Cold start conditions, air relight characteristics and the involvement with calibrations, adjustments, modifications on some models, and handbook changes will be the major sources of impact. Combustors and fuel nozzles in most Air Force engines are designed to meet requirements with either JP-4 or JP-5 fuel. JP-8 should therefore be usable without noticeable effect for most conditions of engine operation. There is a need, however, to test various engines under critical operating conditions to define any impact on ground and flight operations.

b. Altitude Relight

Altitude relight envelope is expected to be reduced by use of JP-8. Although no reduction in the envelope was observed on recent F-4E tests, an effect on the envelope was noted in earlier tests at WPAFB. Slower starts were obtained with JP-8 where starts were successful. It is felt that the length of time between engine shutdown and start initiation made the significant difference in test results. Most present systems surveyed anticipated some degradation in altitude relight capability.

c. Low Temperature Starting

Use of JP-8 will limit low temperature ground starts to approximately -45°F and above depending upon the system. This will apply even after feasible modifications have been made. For lower ambient temperatures, heating facilities will be necessary or else JP-4 will need to be retained. Air Force engines are designed and qualified to start at temperatures down to -65°F with JP-4 fuel. The necessity to start at low temperature extremes is seldom encountered. However, the temperature range over which any given engine can be started is usually degraded by normal deterioration that occurs in the engine, in the starting system, and by the installed effects within the aircraft. The -65°F figure with JP-4 may not be realistic but, likewise, the -45°F range with JP-8 may not normally be attainable and therefore cold weather starting must be considered a major impact.

d. Alternate Fuel Qualification

Alternate fuel capability for an engine model cannot be considered the equivalent of primary fuel capability. Most Air Force engines have been qualified with JP-5 as an alternate fuel. Alternate fuel qualification constitutes high and low temperature testing, endurance testing, some altitude testing, and various engineering tests and analyses attendant to meeting requirements. Once qualified, there must be general usage of the alternate fuel on a common model engine (such as a Navy model using JP-5) to insure that full operational capability is developed and maintained. Only limited confidence can be placed in the use of alternate fuel qualification as a basis for acceptance of a fuel with similar characteristics for general operational use.

e. Smoke Emission

JP-8 has a tendency to smoke slightly more than JP-4. Measurements with J79 low smoke combustor showed about a 5 point increase (per SAE ARP 1179) for JP-5 compared to JP-4. Where limitation of smoke is critical, this may be a factor to consider in determining whether JP-8 should be used.

f. Auxiliary Power Units

Data on airborne and ground auxiliary power units show inability to start, adjust, and accelerate to be the most frequent cause for premature removal. Hot starts and overtemperature are less frequent but still account for significant maintenance actions. These causes for removal occur frequently on some models of propulsion engines also. It is expected that changeover to JP-8 will aggravate these causes for premature maintenance until engines become optimized for the new fuel.

g. Cost of Modifications

Very little cost information can be established covering investigation and modification of engines to become fully operational on JP-8. JP-5 conversion kits have been developed for certain APU's. These run about $300 per unit. Figures developed for propulsion engines in a 1969 study presented costs from $100,000 to $2,500,000 to test and evaluate various models of engines. On J85-5/13/17A engines, combustor and nozzle replacement costs were estimated at $6,000,000. These cost figures need updating and correlation with specific program efforts. OCAMA anticipates changes being required in nozzles, controls, and ignitors. Kit costs as reported in Section VIII total $49 million for the J57 fleet and $10.4 million for TF33 engines. Development would be additional. No estimates have yet been made regarding some of the newer system programs.

h. Commercial Airline Operation

Commericial airlines operate out of a wide range of geographical areas with a JP-8 type of fuel without schedule interruptions due to low temperatures. Explanations for this are that commercial aircraft have low down time so that they do not cold soak as long as military aircraft. When long down time does occur, refueling is delayed until flight time or heated hangars are used. Airlines can also schedule where the aircraft are to be when extended ground time is necessary These practices are not compatible with operational readiness requirements of the military. Also, fuel heaters are used on commercial engines and while they are primarily for prevention of fuel filter icing, they help to maintain temperatures for proper fuel system operation and aid in altitude relights. Only a few Air Force engine models are equipped with fuel heaters. Other differences between commercial and Air Force operations include i -flight refueling and maneuvers or combat operations approaching conditions where stall or flameout occur and relight capability becomes urgent.

i. Ignition System Energy Level

The ignition system energy levels provided on some Air Force turbine engines is substantially less than that for the Navy on the same basic engines. For instance, the J79-8/10 (Navy) system energy is 14 Joules stored/2 Joules delivered compared to 4 Joules stored/0.5 Joules delivered for the J79-15/17 (Air Force). The Air Force design was made necessary by the concept under which the Air Force system must operate - battery powered ignition and cartridge start for self-contained operation.

j. Variables Affecting Starting

Starting characteristics are a function of many variables besides fuel volatility, fuel viscosity, and ignition energy. These variables include fuel control characteristics, fuel nozzle spray pattern and droplet size, fuel surface tension, fuel/air mixture at the ignitor, etc. Starting systems also have various degrees of flexibility. For example, air turbine type starters can be operated for various periods of time but cartridge starters have a fixed energy input.

SECTION IX

IMPACT OF JP-8 ON SPECIFIC WEAPONS SYSTEMS

Presented herein is a review of the impact on specific weapons systems based on assessments by the ASD system program offices (SPO) and by the AFLC Air Materiel Areas (AMA). These organizations were queried by an ASD/ENJ letter dated 27 November 1972. The letter requested that each office identify all impacts which may be expected on their particular system caused by using JP-8 fuel. Definable impacts in the following areas were specifically requested by the letter:

"a. Engine performance, including flameout susceptibility, relight envelope, and time required for relight.

b. Freeze point and volatility effects on ground starting and operation (include information for all current and anticipated mission usage, jet fuel starter, and APU considerations.)

c. Effects on maintenance, including required engine adjustments.

d. Engine (also starter and APU) modification requirements.

e. Engine (also starter and APU) requalification requirements.

f. Estimated cost impact.

g. Exhaust smoke, if this is a consideration on your system.

h. Impact that timing of the switch-over would have.

i. Comments regarding recommendations that the AFSC fleet be operated with Grade JP-8 fuel for a period of time in advance of world-wide use."

Responses are either quoted or paraphrased herein to reflect all anticipated impacts. Correspondence received is identified in the reference list (References 23 through 36).

1. F-4/J79 (Reference 23)

Without conducting a complete flight test, the impact on this system must be generalized. Performance such as thrust and SFC should not be affected by the change in fuel. The engine should be more susceptible to flameout, the relight envelope would be reduced and time for relight increased. The engine ground starting capability should be changed from -65°F to approximately -20°F. The only effect on maintenance expected is an instructional change of fuel density setting. Exhaust smoke is expected to be worse on JP-8 by an average of about 5 smoke numbers. No engine modifications would be required provided the reduced JP-8 envelope, the -20°F cold weather starting limit, and the smoke increase are determined operationally acceptable. A service evaluation on a limited fleet prior to changeover is considered advisable.

2. F-111/TF30 (Reference 24)

The TF30 has logged considerable Navy experience with JP-5 in different applications. The Air Force versions of the TF30 have been qualified for JP-5 and commercial fuels. Various handbooks provide for use of these fuels in F-111 operations. The only concerns would involve low temperature starting (below -40°F) and some slight degradation in airstart Mach/altitude envelope. SPO Engineering estimates that fuel control specific gravity adjustment would minimize such effects. Smoke emissions may increase with JP-8. Burner can improvements to reduce smoke emission have been pursued under Component Improvement Program (CIP) but modifications have not been retrofit. Additional work would be required if the use of JP-8 resulted in an intolerable smoke condition. SPO Engineering summarizes that a switchover to use of JP-8 fuel, under prevailing mission concepts would have little impact on F-111/TF30 operations.

3. A-7D/TF40 (Reference 25)

JP-5 fuel has been used for acceptance test flights of all A-7 aircraft. Based on this experience and analysis of various factors, the A-7D contractor advises that with JP-8 fuel engine performance will be unchanged. No difference in flameout susceptibility would be expected. The relight envelope will be smaller than with JP-4 and larger than with JP-5. The engine exhibits satisfactory relight characteristics on both JP-4 and JP-5 and no problem is expected when using JP-8. JP-8 compared to JP-4 will cause starting problems and system operational problems at very low temperatures. Therefore, if soak temperatures below -25°F are expected, the alert airplanes should be hangered or fueled with JP-4 to permit starting. Starting and operation is satisfactory on JP-5 fuel down to -25°F and is expected to be equivalent or lower on JP-8. The jet fuel starter is qualified for starting using JP-5 and should be satisfactory to the same limits using JP-8. The jet fuel starter is limited to -25°F for low temperature starts. Satisfactory starts and acceleration using JP-5 down to -20°F were demonstrated by NAA/NAPTC, Trenton, NJ, in 1971 using the TF41 engine and the A-7D jet fuel starter. The only maintenance action foreseen is a minor adjustment to the manual fuel control to account for the different specific gravity. This adjustment is made on each A-7D between acceptance flight tests and delivery flight. It is anticipated that JP-8 will be similar to JP-5, and will not cause a smoke problem. In summary no operational problems, other than difficulty in starting at extremely cold temperatures, are anticipated due to the switch-over from JP-4 to JP-8 fuel. The engine contractor's comments are consistent with those of the airframe contractor's except that the engine contractor estimates that the starting capability would go to -45°F. The engine contractor has indicated that tests are required to verify low and high temperature starting and altitude relight capability.

4. C-5A/TF39 (Reference 26)

The use of JP-8 fuel in the C-5A engines and APU's is considered feasible without major modification; however there are some limitations in worldwide operational use when compared to operation with JP-4. Cold temperature ground and altitude starting would be limited to -20°F. A specific gravity adjustment would be used in the fuel control. A normal test and evaluation was conducted with JP-5 fuel during development of the engine to provide JP-5 alternate fuel capability. Tests included cold start, altitude, and endurance running. After an accidental JP-4 fire that destroyed a C-5A some time ago, action was taken to do aircraft factory running and flight checkout with JP-5 fuel. This action identified a relight sensitivity with JP-5 fuel at 30,000 feet on some engines. It was found that certain dimensions in the combustor dome were critical and these are now being checked at overhaul. It is believed that this action is overcoming a relight problem that might have existed at the 30,000 foot altitude. The APU used in the C-5A is the Air Research model GTCP 165-1. In the design of this unit JP-5 was considered as the alternate fuel. The low temperature starting limit on the APU would change from -65°F to -20°F upon switching to JP-5 fuel.

5. F-15/F100 (Reference 27)

No assessment of the impact of JP-8 on the F-15 system of F100 engine has yet been made by the SPO. Hence any impact of JP-8 on F-15 system operations is outside the scope of this report. The F-15 SPO Engineering Director has advised that completion of a JP-8 service test on the F-4 aircraft and examination of the results will provide a realistic base for judging the impact of a fuel change upon the F-15 system.

6. B-1/F101 (Reference 28)

An exchange of correspondence between ASD/ENJ and the B-1 SPO resulted in a statement as follows:

"1. As you are aware, the F101 engine and B-1 aircraft are still under development and it is only possible to speculate on the answer to the questions of paragraph 3.b. of the reference letter. [Freeze Point and volatility effects on ground starting and operation.] The current F101 engine and B-1 airframe contracts require use of JP-4 as the primary fuel and JP-5 as an alternate. Due to the similarities between JP-5 and JP-8, we would expect that the same JP-5 limitations would exist if a change were made to JP-8. Some of these limitations, such as low temperature operation capability, reduced altitude engine relight capability, decreased range due to lower Btu/lb (aircraft weight limited), and difference in pumping characteristics make such a change over look unattractive to the B-1 SPO and appear to be the major areas of impact."

"2. If an Air Force Wide change is made to JP-8, we would immediately have to modify our contracts with both the Airframe Contractor and Engine Contractor to repeat a considerable portion of our combustion development effort for the F101 engine and APU's and, in addition, we would expect additional fuel system testing and development would be required. This would mean added costs which are especially difficult to justify at this time."

7. F-5, A-37, T-38/J85

J85 engine family experience in the military has been almost exclusively with JP-4, except for the auxiliary propulsion application (C-123 and C-119) wherein Avgas is used. On the commercial version of the engine (CJ-610), experience has mainly been with Jet A and Jet A-1 fuels. The J85-13 model used in F-5A aircraft is qualified only on JP-4 fuel. Current efforts are underway to provide alternate fuel qualification on Jet A-1 in compliance with a request from the Malaysian government. The J85-21 model used in F-5E aircraft has JP-5 specified as an alternate fuel but no specific testing has been done under the -21 development and qualification program. The Jet A-1 test work on the -13 engine will apply to the -21 in substantiation of that engine on Jet A-1. The -17A used in the A-37 and the -4 used in the Navy T-2C have both JP-4 and JP-5 specified as primary fuels. However practically all experience on these models has been with JP-4 fuel. The -5 series engines in the T-38 are limited to JP-4 types of fuels. Frequent intentional airstarts are made in these aircraft as part of the training mission. To expand the capability of the T-38 to use JP-8 fuel would require a program of requalification, determination of limits, possible modifications, and appropriate instructions. All J85 applications would be impacted by low temperature start limitations and altitude relight envelope reductions.

8. Drone Systems/J69, J100 (Reference 29)

The following discussion as received from the Drone SPO presents their estimate as to impact of JP-8 fuel.

(1) Typical drone operational modes require air launch preceded by extended captive flight periods in a cold soaking environment. Engine starts are accomplished without starter assist at an engine speed of 4 to 5 percent and 18,000 to 22,000 ft. This is currently the physical engine starting limit using JP-4 and tests with JP-5 show a marked degradation. Presumably the starting capability with JP-8 would be closer to the JP-5 capability and would in any event be much reduced for the current JP-4 start regime. Such a mission degradation would be unacceptable.

(2) Flameout susceptibility at lower altitudes should be no problem but at the very high altitude flight conditions, with combustor pressures of 3 to 5 psia which have been previously tested, it would be necessary to retest to verify. No relight capability exists in the drones and once the light is out, the bird is lost.

(3) High altitude, long endurance flights could prove to lower fuel temperatures in the wing tanks to nonflowable conditions. Past experience has indicated ambient conditions as low as -120°F.

(4) Some drone engines have an external density adjustment on the fuel control which could compensate for the JP-4 to JP-8 change. The ones which do not would require internal changes which could be done only at overhaul.

(5) Ground starting capability would be degraded as well as altitude starting. The drone engines do not have automatic start sequencing and depend on operator expertise to properly start without damaging over temperatures. Any starting degradation will tend to increase damaging start conditions and increase maintenance.

(6) Exhaust smoke is not a factor.

(7) Cost impact cannot be estimated at this time.

(8) JP-8 use in drone systems is considered extremely impractical in some applications and only undesirable in others.

9. AGM-86A (SCAD) System (Reference 30)

Comments of the AGM-86A SPO are presented to show the impact of JP-8 on that system. Note that a significant change is needed in the low temperature viscosity requirement of the fuel in order that specified requirements for the vehicle are met. Otherwise, JP-8 would have a beneficial effect on range and no foreseeable impact on other characteristics of the system. For planning and management purposes, an early implementation of JP-8 fuel usage would be helpful if JP-8 is to be adopted. Note also that use of low volatility fuel in the development program is limited to critical points. Early implementation would increase general test usage and identify problems at an earlier date. Comments of the AGM-86A SPO engineering are quoted:

"(1) The AGM-86A Program Office, in anticipation of a requirement to convert to JP-8 fuel, established a requirement in the engine contracts to include the capability to use JP-5 fuel. Testing during engine development using JP-5 is limited to proof at critical operating conditions only, such as low temperature, high altitude starts, etc., with a majority of the tests being accomplished on JP-4. Accordingly, we anticipate no major problems in contractually implementing a change from JP-4 to JP-8.

(2) Current specification requirements relating to the freeze point would severely restrict SCAD operation since SCAD is air carried and air launched. A freeze point not higher than -65°F is required for SCAD. Also, current SCAD engine specifications carry a start limitation of 12 centistokes. Although we have not tested these engines at low temperatures to determine if they have a capability greater than 12 centistokes, the current specification requirement is limiting. Accordingly,

the viscosity requirement should be revised to a requirement that viscosity will not be greater than 12 centistokes at -65°F.

(3) Other comments are as follows:

(a) Since SCAD is a volume limited vehicle, approximately a 5% increase in range would result from the conversion.

(b) No logistic impact is anticipated.

(c) Cost would not be a significant factor.

(d) We have no hard requirement on exhaust smoke.

(e) Since we are in development, the sooner a decision is made, the better. However, the next major milestone data is QT development that starts approximately 1 October 1973."

10. A-10/TF 34 (Reference 31)

Initial SPO response indicated that performance, design, and cost impacts would require contractor evaluation. Desire was expressed for a flight test evaluation to determine operational characteristics such as air starts and smoking tendencies. It was felt that use of JP-8 would have only moderate to minor impact on the aircraft's fuel system. The A-X aircraft are required to meet the Survivability/Vulnerability (S/V) requirements with JP-4, however, JP-8 would probably provide additional benefits such as reduced structural damage from gunfire and improved suction feed performance. No unique cold temperature problems could be identified for the A-X fuel system. A test program of considerable magnitude would be required to realize any S/V benefits or to verify fuel system performance using JP-8. Additional information from the contractors is forthcoming and will be incorporated as soon as available.

11. UH-1N/T400 (Reference 32)

There has been considerable experience with JP-5 on Navy engines and with Jet A-1 on the commercial application. The experience with these fuels indicates that there should be no problems in the use of JP-8 except that cold weather starting and the higher freeze point will dictate certain limitations in its use. Starting is limited to the temperature at which the fuel reaches 12 centistokes viscosity.

12. AWACS/TF33 (Reference 33)

Based on commercial engine experience, no significant effects on engine performance are expected in switching over from JP-4 to JP-8. The engine manufacturer reports that no problems have been encountered in commercial experience with the engine due to freeze point under extended cruise conditions at high altitude (35,000 to 40,000 ft and occasionally higher). JP-8 fuel tends to result in poorer ground engine starting characteristics compared to JP-4. The low temperature limit for ground starting with JP-8 has not been indicated. The bare engine specification low temperature starting limit was -65°F on that temperature corresponding to 12 centistokes for the fuel used. In the AWACS application the engine is being subjected to considerable modification and will be burdened with relatively heavy accessory drag during start. The system requirement is to operate to -65°F, but the starting capability of the installed engine will have to be evaluated. JP-8 would have a greater smoke tendency in this application, although the difference may be small. Cold weather ground start and flight test with JP-8 fuel would be considered with this aircraft.

13. AMST (Reference 34)

The advanced medium stol transport (AMST) will use existing commercial engines that presently use Jet A-1 fuel. Hence JP-8 should have no impact on this system.

14. Lightweight Fighter (Reference 34)

The YF-16 uses the F100 engine as used in the F-15 aircraft except for modifications applicable to the YF-16. JP-5 is treated as an alternate fuel in the F100 engine. It is expected that the usual JP-5 low temperature start limits and altitude restart limits will apply. The YF-17 uses the YJ101 engine which is being developed through prototype preliminary flight rating test using JP-4 fuel. JP-8 could be specified for any follow-on development program if the switch is made.

15. OCAMA Engines (Reference 35)

The OCAMA study reflects that extensive testing will be required to accurately define the effects of using JP-8 fuel in propulsion and starter systems designed for JP-4 fuel. Their study also considered that (1) costly and extensive fuel system and ignitor system modifications would be necessary, (2) ground and flight operational restrictions should be imposed unless modifications are made, and (3) aircraft mission requirements such as range, weight, and takeoff distance will be changed. OCAMA recommended that consideration be given to the use of JP-8 fuel for only growth engine models and new propulsion systems. The OCAMA comments in respect to specific questions were as follows:

(1) Engine performance, including flameout susceptibility, relight envelope, and time required for relight: Basic engine performance parameters would not be changed by the use of JP-8 fuel instead of JP-4 fuel if the main fuel control is changed to provide the required fuel schedules. However, the engine would be more prone to flameout using JP-8 fuel than JP-4 because JP-8 fuel is less volatile. No information is now available concerning the relight envelope and the time required for relight using JP-8. Engine testing would be required to develop this data.

(2) Freeze point and volatility effects on ground starting and operation (current and anticipated missions): Both ground and flight operational restrictions will probably be imposed on aircraft with the use of JP-8 fuel. Harder cold weather and altitude starts will be

experienced since JP-8 is heavier and less volatile than JP-4. The fuel will not enable Air Force engines and starters to meet the specification requirement for a -65°F cold start; therefore, ground operational restrictions will probably be imposed in certain cold weather locations (i.e., Alaska, Greenland). Flight operational restrictions will be imposed on aircraft that presently fly at altitudes above 31,000 feet. Above this altitude the outside air temperature (OAT) is below the freezing point of JP-8 fuel.

(3) Effects on maintenance, including required engine adjustments: Full impact on maintenance requirements cannot be determined without full scale engine and starter testing but because of the higher density of JP-8 the engine and starter main fuel controls (MFC) will require retrimming and/or modification to provide the required fuel schedules. Age and overhaul equipment such as accessory test benches may also require modification because of the use of higher density fuel. It is also suspected that more frequent engine hot section inspections will be required because of hot section distress caused by carbon deposits from incomplete burning of high density fuels.

(4) Engine (also starter and APU) modification requirements: The required engine modifications to correct foreseeable problems consist of:

(a) Redesigned main fuel controls

(b) Higher Joule ignition systems

(c) Redesigned afterburner fuel controls

(d) Redesigned fuel nozzles and manifolds

Items (a), (b) and (d) would also have to be modified on the starters.

(5) Engine (also starter and APU) requalification requirements: Requalification of the engine using full scale engine testing

to the requirements of specification MIL-E-5009D and aircraft flight testing would be required to:

(a) Determine and define required changes to engine and starter model specifications, engine and starter components, and performance curves.

(b) Demonstrate cold start capabilities, altitude relight envelope, and time required for relight.

(6) Estimated cost impact. The estimated cost of change over on OCAMA prime engines, which consists of the F101, J33, J47, J57, J71, J79, T58, T64, TF30, TF33 and TF41 would be large. For example, the cost of designing engine component changes and bench testing for the J57 engine would be approximately $250,000 and about $200,000 for the TF33 engine. Part qualification testing requirements, as per MIL-E-5009D, for the two engines would be approximately $450,000. Cost of retrofit of the required engine changes would be approximately 49 million dollars for the J57 engine and 10.4 million dollars for the TF33 engine. Cost breakdown on these engines is as follows:

ENGINE TYPE	ENGINE COMPONENT	STOCK LIST PRICE	COST OF MODIFICATION OR REPLACEMENT
J57	Ignitors	$1,038	$ 500
	Main Fuel Control	$9,200	$1,000
	A/B Fuel Control	$2,500	$2,000
	Fuel Nozzles	$2,400	$2,400
			$5,900/engine
TF33	Ignitors	$1,038	$ 500
	Main Fuel Control	$9,200	$1,000
	Fuel Nozzles	$2,400	$2,400
			$3,900/engine

(7) Exhaust smoke, if this is a consideration on systems in question: Exhaust smoke is a concern on OCAMA engines but as of this time no AFLC direction or funding support has been provided to alleviate the problem.

(8) Impact that timing of the switchover would have: If the total switchover occurred after the modification and requalification requirements are complied with, the impact should be no greater than the cost impact stated above. If an accelerated switchover occurs, the cost will be substantially increased.

(9) Comments regarding recommendations that the AFSC fleet be operated with JP-8 fuel for a period of time in advance of world-wide usage: The AFSC fleet should be used to conduct comprehensive, full scale engine tests, aircraft flight testing, and accelerated endurance engine static tests. Upon satisfactory completion of the preliminary evaluation of the JP-8 fuel, the test results should be forwarded to engine AMAs for review. The results will enable the engine AMAs to more fully determine the specific engine hardware modifications required.

(10) Other areas of impact: The use of JP-8 fuel will also have an impact on aircraft mission requirements such as range, weight, and take-off distance because of the increased density of the fuel. The higher freezing point of JP-8 fuel will also dictate the use of aircraft fuel tank heaters to prevent freezing of the fuel above 31,000 feet or additional antifreezing additives."

16. OOAMA Systems - F-4 and F-101 Aircraft

Ogden Air Material Area advised that they would concur in a recommendation that the AFSC fleet be operated with JP-8 fuel for a period in advance of world-wide use. Ogden AMA also advised that they were working closely with OCAMA relative to impact on J79 and J57 engines.

17. SAAMA Systems (Reference 35)

Position statements were presented by the Director of Aerospace Fuels, 24 Jan 73, and by the Deputy Director for Materiel Management, 2 Feb 73. The Director of Aerospace Fuels stated that his position remains as presented in the SAAMA/SF Staff Study, 25 Jan 72. He further noted that segregated base supply fuel systems will have to be maintained if the AFSC fleet is operated with JP-8 fuel in advance of world-wide use.

This will be necessary to permit servicing of JP-4 to transient aircraft not in the pilot program. The Deputy Director for Materiel Management (SAAMA/MM) summarized concerns expressed in their June 1968 letter as to impact in the areas of (1) cold weather starting, (2) altitude relight capability, and (3) fuel control acceleration scheduling. SAAMA/MM considered that information presently available does not permit an accurate assessment of whether these factors can be compensated by trim adjustments or will require modification of fuel controls and/or ignition systems. SAAMA/MM further recommended that suitable ground and flight tests be devised, possibly followed by controlled service tests, so that the impact of fuel conversion may be derived on each aircraft application.

18. SMAMA Systems (Reference 35)

Sacremento Air Materiel Area (SMAMA/MM) responded to the various impact areas questioned and offered some additional considerations. SMAMA noted that all changes necessary would become evident only through actual test. The expected impact on SMAMA systems would include the following:

(1) Engine performance - Acceleration would be faster, EGT higher, and fuel flow greater until engine is correctly adjusted for JP-8 use.

(2) Engine starting and operation - Ground and air start envelope at low temperature decreased. In extreme cases, ground starts may require warming of the aircraft and fuel. Air starts of single engine aircraft that are prone to compressor stalls or flameouts will be critical. None of the SMAMA aircraft are prone to flameouts.

(3) Maintenance - Trim settings will not change.

(4) Modifications - None anticipated.

(5) Requalification - No new engine operating parameters.

(6) Cost, exhaust smoke - No comment.

(7) Timing of switchover - Impact will depend on results of tests. Anticipate that field and organizational maintenance should be able to accomplish all required changes.

(8) Fleet test - Trial period in CONUS to completely determine effects.

(9) Additional considerations:

(a) A change in dielectric constant of the fuel makes adjustment and calibration of the fuel gaging system necessary. It is not known whether the zero and full adjust can compensate for this or if modification of the gaging systems will be required.

(b) Retention of additional fuel by the fire suppression foam installed in some aircraft must be checked. The higher viscosity and possible higher surface tension of JP-8 may cause increased fuel retention by the foam and result in an increase of unusable fuel.

(c) Greater pressure drops within the fuel system plumbing due to the higher viscosity of JP-8 must be considered because of the possible effect on fuel transfer and fuel feed.

19. WRAMA Systems (Reference 35)

Warner Robins Air Materiel Area (WRAMA/MM) expressed comments concerning service manuals and fleet evaluation as follows:

(1) There can be a substantial cost to WRAMA in the updating of T.O.'s if JP-8 becomes the primary fuel for Air Force aircraft. Required changes to T.O.'s may appear to be minor; but, a change in primary fuel will change the data basis for aircraft performance charts from flight test to estimated. When the accuracy of estimated data is questioned, flight tests are required to verify its accuracy. Aircraft/engine maintenance and service manuals will also require changes if JP-8 becomes the primary fuel.

(2) Operating the AFSC fleet with Grade JP-8 fuel for a period of time in advance of world-wide use could provide advance information on potential problems. The value of this information can be greatly improved if AFSC treats this period of time as a test program by developing a test plan and instrumenting the aircraft.

(3) If JP-8 is eventually going to be the primary fuel for military aircraft, it should be used as the preferred alternate for a period of time. This would provide advance information on a wider cross section of engines than could be obtained using the AFSC fleet.

20. AGE Systems (Reference 36)

The ASD Directorate of Crew and AGE Engineering has reviewed three areas where a switchover to JP-8 fuel may impact AGE systems. These are discussed as follows:

(1) Fluid handling/generation

(a) Although fuel filtration equipment is tested with JP-5 fuel, it is recommended that the military standard/filter/separator element in accordance with MIL-F-52308 be subjected to complete qualification tests in accordance with MIL-F-8901 at the Mobility Equipment Research and Development Center (MERDC) U. S. Army facilities. Cost for such a test would be approximately $20,000 plus cost of the fuel. Scheduling would have to be worked out with the Army. Such action would verify that the present filtration equipment is capable of safely servicing JP-8 fuel. This equipment is used AF wide to support all weapon systems.

(b) The A/M26U-1 liquid oxygen/nitrogen generating plants, manufactured by Cosmodyne Corporation, uses an Airsearch Model 100-54 bleed-type gas turbine to furnish compressed air and electrical power to operate the generating plant components. Since the equipment is designed for JP-5 operation, use of JP-8 should not be a problem. The A/M26U-1 is a general support item.

(2) Vehicle Maintenance. Wide use of JP-3 in lieu of JP-4 should not affect the equipment in this area.

(3) Electrical Power Generation.

(a) The EMU-29/30 turbine powered generator sets, manufactured by Solar Division of International Harvester, are designed to use JP-4 fuel. It is estimated that conversion to JP-8 fuel operation would cost approximately $300.00 per unit based on contractor information to convert to JP-5 fuel. Generally, the changes involve the flame tube, fuel atomizer and flow divides, ignition unit, and fuel control. The approximate number of units that will be in the inventory by 1 July 1973 is 1100. These units are used for support of the 407L Weapon System (Air Weapons Control System).

(b) The diesel engine generator sets can operate on JP-4 fuel only on an emergency basis for 200 hours. The use of JP-8 in lieu of JP-4 fuel should also be restricted accordingly.

SECTION X

FUEL HANDLING AND MAINTENANCE

Ground safety would be improved considerably with JP-8. Most operations are at temperatures below the 105°F minimum flash point of JP-8. Specific operations which would benefit are:

Purging
Hot Refueling
Switch Loading
Maintenance

Purging of aircraft tanks to remove JP-4 vapors in preparation for hangar maintenance, other than for repair of fuel systems, could possibly be eliminated. Purging fluids cost about $100,000 per year. The cost of performing the purging operation is additional and would have to be evaluated by AFLC elements (Kelly, Tinker, etc.). Maintenance that does involve fuel system entry and repair would become safer with JP-8, particularly depuddling of aircraft tanks. Time for blow or exhaust purging would be shortened if required at all (Reference 37).

Switch loading, i.e., changing refueling vehicles from one product to another product of higher or lower volatility would be simplified at sites where JP-4 and JP-5 are in frequent use. The necessity to remove JP-4 vapors would be eliminated. Perhaps fewer refueling vehicles would be required with attendant cost savings. However, during the conversion period from JP-4 to JP-8, special procedures and operations involving switch loading aircraft will need to be developed and enforced.

Hot refueling, as practiced by TAC, involves refueling at ramp pit locations, with one engine running on multiengined aircraft. Elimination of JP-4 vapors would enhance safety of such operations.

Ground operations and maintenance in general will be safer with JP-8 due to elimination of JP-4 vapors which can propagate flames from ignition sources to the bulk fuel. Realization of this safety advantage is, contingent on the continued rigorous adherence to established safety procedures.

The C-5A fire at Marietta, Georgia in 1970 has focused increased attention on ground safety and precipitated actions (References 38 and 39) to upgrade facilities and equipment to comply with regulations (Reference 40). The cost of this compliance is unknown at this time.

Incidents at government owned or supported facilities involving JP-4 and an ignition source, such as static electricity or ground equipment, are summarized in Table XVI. Many, perhaps all, of these incidents would not have occurred with JP-8.

TABLE XVI

GROUND EQUIPMENT AND PERSONNEL LOSS DUE TO FUEL RELATED INCIDENTS

DATE	EQUIPMENT	PERSONNEL FATALITIES OR INJURIES
Jan 66	Commercial transport	None
Mar 66	F-6 refueler	1
Sep 66	C-141 aircraft	3
Feb 68	Two 5000 barrel tanks	2
Jan 69	F-6 refueler	1
Feb 69	20,000 barrel tank	1
Mar 69	Commercial refueler	1
Dec 69	Commercial transport	2
Jan 70	A-4 aircraft	1
Feb 70	TH-1S helicopter	1
Jul 70	B-52 aircraft	None
Aug 70	F-84F aircraft	None
Oct 70	C-5 aircraft	1
Dec 70	F-4 aircraft	1
Dec 70	R-2 refueler	None
Jan 71	Commercial transport	None
Jul 71	C-141 aircraft, two R-5 refuelers	None

SECTION XI

ENVIRONMENTAL IMPACT

1. RAW VAPOR EMISSIONS

Conversion to JP-8 would virtually eliminate the hydrocarbon vapor emission problem and would result in compliance with applicable government regulations (References 41 and 42).

A previous study (Reference 21) identified construction requirements in order to comply with regulations as follows:

$17,400,000 - Install floating pans in tanks over 40,000 gals.

$ 7,000,000 - Install vapor emission control devices on truck fillstands dispensing over 20,000 gallons/day.

A more recent study (Reference 43) addressed the problem of vapor recovery from aircraft and mobil equipment (refueling vehicles) and measurement of emissions, the latter to establish that, in fact, compliance is achieved. The funds indicated above for fillstand control devices are for hardware procurement. The developmental cost was not included and the actual design required is unknown.

Funds for procurement and installation of vapor control equipment for aircraft and refueling vehicles have not been identified to date. Implementation of a vapor control program can be expected to be costly.

2. ENGINE EXHAUST EMISSIONS

Engines will tend to emit more smoke with JP-8 than with JP-4. Oxides of nitrogen emissions are expected to be the same for JP-4 and JP-8 since nitrogen oxide concentration depends on cycle temperature, not on fuel properties. Unburned hydrocarbon and carbon monoxide emissions at idle power are expected to increase slightly with JP-8 compared to JP-4. The degree of the effect is dependent on combustor design and conditions so a quantitative statement is not made here. Reference 44 reviews the subject in detail.

SECTION XII

STANDARDIZATION, FUEL COST, AND AVAILABILITY

1. STANDARDIZATION AND INTERCHANGEABILITY

a. Army

The Army uses 5% of the JP-4 procured by the DoD. Logistics and collocation of operations dictate that the Army and the Air Force use the same fuel. The Army has informally expressed strong interest in converting to JP-8. However, they cannot independently convert due to the common usage aspect.

The Army is particularly interested in crash survivability of helicopters. They have developed crash-survivable fuel systems which employ self-sealing techniques and reduce the quantity of spilled fuel involved in post crash fires. Escape potential is increased and would be increased further by using JP-8 as reflected in Section V.

The Army maintains interest in improving safety by using modified fuels, specifically the anti-misting additives. Modified fuels are effective if, and only if, the vapor hazard is eliminated. Grade JP-4 cannot be modified to suppress the vapor hazard. Grade JP-8 must be used as the basic fuel for modification.

b. Navy

The Navy uses JP-5 on shipboard but uses JP-4 at land bases. Most Navy systems are designed to operate on JP-5 fuel and will operate on JP-4 and JP-8 fuel without modifications or flight test. Their land based operations would not be affected by conversion to JP-8 which has properties intermediate between JP-4 and JP-5.

The Navy has re-examined the minimum 140°F flash point requirement for fuel stored and handled aboard ship, and the study has confirmed that fuels having a flash point below 140°F presented an unacceptable fire and explosion hazard. Based on this study and a corollary cost study, the Navy has reaffirmed that JP-5 fuel is a military requirement aboard ship.

c. NATO/Air Standarization Coordinating Committee (ASCC)

Australia, New Zealand, the United Kingdom and France are the only member countries currently using JP-8 type fuel. All others are using JP-4 type fuel. Table XVII reflects current usage along with variations in additive requirements.

Fuel System Icing Inhibitor (FSII) and corrosion inhibitors are used almost universally in both JP-4 and JP-8 equivalent specifications. Australia prohibits the corrosion inhibitor. Static dissipator additive is allowed in U.K., Canadian, and New Zealand fuel. The U.S. permits use of fuel containing this additive on an occasional uplift basis.

TABLE XVII

CURRENT FUEL AND ADDITIVE USAGE BY NATO AND ASCC MEMBERS

Members	Primary Fuel Type	Corrosion Inhibitor	Static Dissipator	FSII Vol %
Australia	JP-8	Not allowed	Not allowed	0.10-0.15
U.K., New Zealand	JP-8	Hitec E515 only	ASA-3 allowed **	0.10-0.15
Canada	JP-4	Allowed, not specified	Allowed, not specified **	0.10-0.15
France	JP-8	Hitec E515 only	ASA-3 authorized	0.10-0.15
Germany	JP-4	Hitec E515 only	Not allowed	0.10-0.15
Italy	JP-4	Hitec E515 only	Not allowed	0.13-0.16
All others including U.S., Belgium, Denmark, Greece, Netherlands, Norway, Portugal and Turkey	JP-4	Required per QPL 25017	Not allowed	0.10-0.15

**Conductivity specified

At the June 1972 NATO Working Party Meeting on Fuels, etc., France recommended that NATO members consider adopting F-34 (JP-8) fuel in lieu of F-40 (JP-4) fuel. France conducted a study, as did the U.S., to determine in-flight and ground safety advantages, economics, and technical aspects for conversion from F-40 to F-34 fuel. At the June 1973 meeting France announced that they would convert to F-34 on August 1973 and that F-40 usage would be eliminated. This was accomplished. At the June 1974 meeting the NATO nations agreed that the preferred military fuel should be F-34 and that nations should proceed with conversion from F-40 to F-34 when fuel supply improved and operational limitations experienced by certain aircraft with F-34 had been overcome. Italy is scheduled to convert to F-34 in 1977.

Interchangeability of JP-8 type fuel specifications is given in Table XVIII. There are no serious specification related problems that would preclude conversion to JP-8. The only departure worth discussion is the 20% point for distillation. The foreign specifications require at least 20% distilled at 392°F. This essentially forces higher volatility in the low temperature boiling range. However, the fuel still meets the JP-8 specification in the low boiling range.

d. Commercial Airlines

Conversion to JP-8 will place the DoD in direct competition with the commercial airlines for kerosene type product. Grades JP-8, Jet A, and Jet A-1 have the same distillation temperature range. Civil aviation domestic consumption reached 13 billion gallons in 1974 while availability was projected at 19 billion gallons (Reference 45). If the DoD consumes 5 billion gallons annually the kerosene market would become very tight. The projection was based on U.S. SST and Concorde demands which have not materialized. The main conclusion is that the DoD must phase in conversion gradually in order to minimize availability and cost problems.

TABLE XVIII

INTERCHANGEABILITY OF F-34 (JP-8) FUEL SPECIFICATIONS

Country	Specification	Deviations from U.S. Specification
U.S.	Proposed MIL-T-83133	-58°F max. freeze, 105-150°F flash, 25% max aromatics, 550 end point
U.K., Denmark, New Zealand	D ENG RD 2453 Issue 3 (AVTUR)	1. Only 20% at 392°F, End point specified. 2. 100°F min flash (IP 170) 3. -58°F max freeze 4. 20% max aromatics 5. Hitec E515 only, ASA-3 allowed.
Australia	DEF(AUST)240A	1. Only 20% at 392°F, 572°F end point specified. 2. 100°F min flash (IP 170) 3. -58°F max freeze 4. 20% max aromatics 5. Corrosion inhibitor not allowed.
Canada	3-GP-23g	1. Only 20% at 392°F, 572°F end point specified. 2. 103°F min flash (D56) 3. -58°F max freeze 4. 22% max aromatics 5. Corrosion inhibitor not allowed.
France	AIR 3405C	1. Only 20% at 392°F, 550 end point specified. 2. 106°F min. flash. 3. -58°F max. freeze. 4. 20% max. aromatics. 5. Hitec E515 only, ASA-3 allowed.

Note: Other NATO members would be expected to adopt the U.S. specification.

2. FUEL COST

Costs of all fuel drastically increased late in FY-73 and continue to be unpredictable. Consequently, it has not been possible to estimate a reasonable total fuel cost and a difference in cost between JP-4 and JP-8. There are some qualitative observations that are worth noting which will persist as considerations in any conversion to JP-8.

The basic difference in composition between JP-4 and JP-8 is that JP-4 contains roughly one-half naphtha, i.e. a low boiling fraction common with gasoline. The Department of Interior (DOI) study of 1971 (Reference 46) cited some extremely important factors which would act to drive JP-4 cost to the point where it would be a "premium" rather than a "cheap" fuel. These factors, reinforced, not weakened since 1971, follow:

a. Increased demand for naphtha to produce synthetic natural gas.

b. Increased demand for naphtha for reforming to produce low lead gasoline.

c. Increased naphtha demands for petrochemical feedstocks.

It is entirely possible that no change in fuel cost will be involved in converting to JP-8. This is based on the speculation that, due to the demand for naphtha, costs will rise faster for JP-4 than for middle distillate fuels such as JP-8 and that all fuels will be subject to the same transportation costs. It is also assumed that conversion to JP-8 would be phased over a 3 year period so that the refining industry could gradually adjust to the change in fuel types.

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